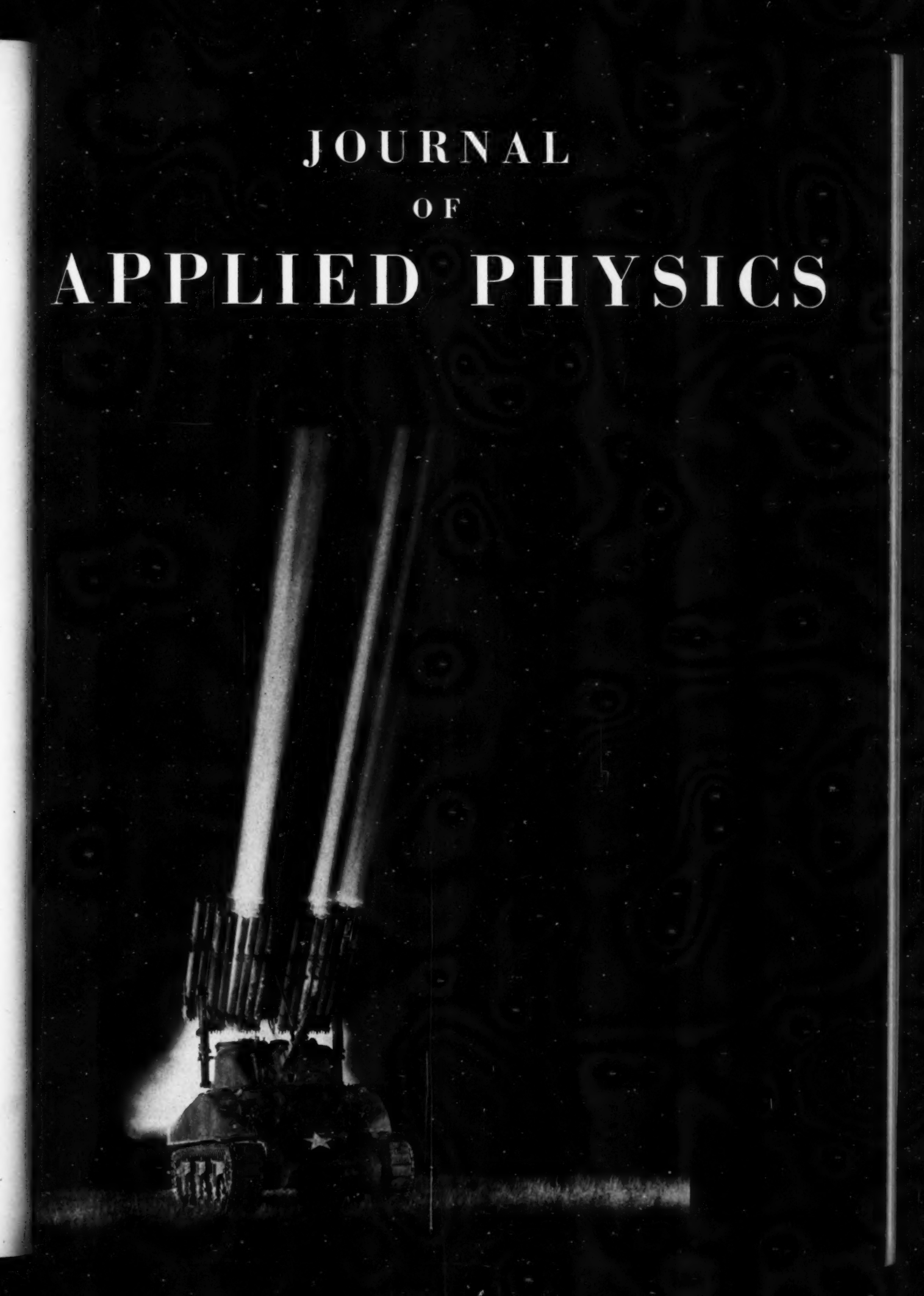
JOURNAL OF APPLIED PHYSICS



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Research and Development in the Ordnance Department, U. S. Army

RESEARCH AND DEVELOPMENT SERVICE

By Major General G. M. Barnes

Ordnance Department, Chief of The Research and Development Service, Office Chief of Ordnance, Army Service Forces

Major General G. M. Barnes

THE mission of the Research and Development Service is defined by the Chief of Ordnance in his order organizing this Service, which states:

"The general function of the Research and Development Service is to plan and execute forward-looking programs of research and experimental development of new and improved Ordnance materiel and new and improved materials for Ordnance use. . . . The execution of these programs will be planned . . . to insure that the existing organization and facilities throughout the Ordnance Department, the Government, and industry are most effectively utilized. . . . The Research and Development Service will retain responsibility for and control of such programs through the stages of basic research, technical research, and experimental development, . . . and until the item is standardized (or until the project is abandoned)."

This mission includes direction, coordination, and supervision for the entire Ordnance Department of all activities relating to research and development; including the acquisition, evaluation, and application of Ordnance technical intelligence both foreign and domestic; complete liaison and close cooperation with using Arms and Services, with the Navy Bureau of Ordnance, and with every resource of science, technology, and invention which can be utilized by Ordnance for research and development.

Close integration of Ordnance research and development with the succeeding stages of procurement, storage, issue, maintenance, and obsoletion is provided by the internal organization of the Ordnance Department.

All Ordnance research and development has for its objective new or improved Ordnance materiel. The creation and evolutionary development of even a single new weapon is an undertaking which requires the directed, coordinated, and combined efforts of many men. The simultaneous development of the nearly two thousand different major items of Ordnance materiel is an undertaking of extreme complexity and very considerable magnitude, which depends for its direction and coordination upon the Research and Development Service.

Personnel of this Service must be multilingual in that they must understand and speak the language of soldier, scientist, engineer, technologist, and industrialist. They must know and be able to translate to the others the needs, capabilities, and limitations of each. They must direct and coordinate a vast cooperative exchange of ideas, information, and effort, while

FIG. 1. Organization of Research and Development Service.

formulating and allocating the specific objectives to be attained.

Within the Research and Development Service itself is performed that part of its work so highly specialized as to have no counterpart outside. This includes the gathering and utilization of technical intelligence; ballistic research and the preparation and application of ballistic data; and above all the general coordinated layout of design for each piece of new or improved materiel. It includes also the selection of Ordnance materials, and the control of Ordnance quality through specifications. Within this Service known or anticipated military needs are correlated with the capabilities and limitations of all resources available to meet these needs; and here are initiated, usually in advance of actual military demand, the plans and designs which will eventually become the detailed working drawings of proven and standardized materiel ready for the processes of quantity manufacture.

The most vital internal function of the Research and Development Service is that of foreseeing, predicting, and preparing for future military needs which cannot be satisfied by existing materiel or sometimes not even by known applications of presently known principles. This involves the incessant study of military and other intelligence for trends; and the constant formulation and placing of programs of research to secure the necessary design data and of programs of experimental development to apply this data in new designs which will be held in readiness for the need when it actually appears. By vigorous and farsighted exercise of this function every need so far has been met.

The Research and Development Service is organized and staffed for the performance of its interior functions and for the efficient maintenance of its many and varied external relations. The staff, both military and civilian, includes ballisticians, physicists, chemists, mathematicians, engineers, and experienced designers for each class of materiel. Very great use is made of consulting and advisory staffs which include many of the foremost American scientists, engineers, and industrialists.

The internal organization is composed of a headquarters, an Executive Division, the Research and Materials Division, and six materiel Development Divisions which cover the entire field of Ordnance materiel (see Fig. 1).

Partly within and partly external to the Research and Development Service is the important Ordnance Technical Committee, operated by this Service, meeting once each week, and forming the vital operating link between the work of Ordnance research and development and the needs of the Armed Forces.

This Committee is composed of representatives

of all Services of Ordnance, other Technical Services of the Army Service Forces, Army Ground Forces, Army Air Forces, Navy, the various using Arms, and our Allies. The general function of the Committee is "to consider and recommend technical action upon all matters affecting materiel designed for and intended to be issued to the Armed forces, coming within the jurisdiction of the Ordnance Department and upon such matters as may be referred to it by the Chief of Ordnance."

Through this Committee the using Arms express their desires and needs as to new and better equipment; have a definite voice as to the characteristics and functioning of contemplated or proposed materiel; and are in position to accept or reject a newly developed item before it is standardized and goes into full production.

The external work of the Research and Development Service is that of utilizing, for Ordnance research and development, and as completely and intelligently as possible, the vast resources which lie outside the Ordnance Department. So thorough is this work that it is certain that no important resource is overlooked, and exploitation of each is now as complete as is permitted by the extreme war pressure for immediate specific results.

The resources of military and civil information are actively used. Innumerable advisory, consulting, and working contacts have been made in every field with the individuals best fitted to aid on specific problems. Thousands of contracts on projects ranging from broad generic research through large to small items of experimental development have been entered into with those organizations in the fields of education, science, engineering, technology, and industry best fitted to carry them out.

The external relations of the Research and Development Service are actively maintained from within the Service by every means of communication, ranging from the personal conferences between those who guide the policies to the follow-up in detail by the project officer assigned to each individual project, and including the personal liaison between this Service and related agencies.

Too great tribute cannot be paid to the magnificent outside cooperation which this Service receives, and without which the full accomplishment of its mission would be impossible.

Looking to the future security of the United States, it is our hope that, through the constructive mutual planning now under way, means may be found to maintain through the years of peace, although on a smaller scale, the same interest and cooperation now so generously extended to the work of Ordnance research and development.

RESEARCH—ITS COORDINATION AND APPLICATION IN THE DEVELOPMENT OF ORDNANCE MATERIEL

By Colonel Scott B. Ritchie

Ordnance Department, Assistant Chief, Research and Development Service, and Chief, Research and Materials Division

RESEARCH in Ordnance is vital to our national security. The scope and quality of research and the efficiency with which it is applied determine the eminence of our Ordnance materiel and the success of our troops in battle. Development of Ordnance weapons and equipment has been built on a firm foundation of research—basic, technical, and applied—carefully coordinated into specific development programs. This includes not only research in the usual abstract academic sense, but also a broad program of research into materials—iron, steel, rubber, plastics, chemicals, fuels, and lubricants; an Ordnance technical intelligence organization for the collection of data on foreign and domestic practice; and the application of special testing techniques and instrumentation peculiar to the development of Ordnance materiel. Certain features of this extensive activity are outlined in greater detail in other articles in this issue of the Journal.

Ordnance research is not an end in itself, nor is it alone sufficient. Through the Science-Industry-Ordnance Team work, so effectively advocated by the Chief of Ordnance, Lieutenant General Levin H. Campbell, Jr., and so cooperatively supported by Science and Industry, the Ordnance Department, Army Service Forces, has been able to utilize and to apply the great scientific and industrial research facilities in this country with their scientific and engineering talent in the solution of Ordnance problems involved in the development of Ordnance materiel.

Research peculiar to Ordnance is conducted for the definite purpose of obtaining principles and design data which eventually appear in the finished item or weapon. New weapons and other Ordnance materiel are composites of coordinated and applied thought, knowledge, skill, equip-

ment, materials, and effort. For practical purposes, the following general statements of Ordnance research and experimental development into which it leads may be used:

a. Basic research is directed toward the discovery, formulation, and application of principles.

b. Technical research is directed toward the solution of immediate specific problems arising in the course of experimental development. It includes with scientific and technological work the gathering of technical information.

c. Experimental development is conducted under individual projects, each directed toward the ultimate standardization of a particular item of new or improved materiel designed to anticipate or meet a military need. Such projects begin when knowledge and creative thought are crystallized in a preliminary design, and continue with the aid of incidental research and engineering skill until the project is successfully completed or is abandoned.

Thorough coordination assures complete coverage of the subjects on which new knowledge is needed, the proper allocation of work, optimum concentration of effort, rapid interchange of information, prevention of undue duplication, and immediate application of results to the problems at hand. A clear understanding of Ordnance problems is essential for coordination. This leads to definite statements of the kind and extent of knowledge desired, and to the formulation of programs of research and development, to the allocation of these programs to those facilities best fitted to carry them out, and to constant supervision of programs, funds, and work under way to insure complete and efficient coverage and immediate application of results.

A primary function essential in coordination and application of research is the maintenance of a network of rapid and complete communication between all research activities under way, and the experimental development which utilizes the results of this work. This network is effectively maintained by liaison personnel, operating between the Research and Development Service of Ordnance and the Research and Advisory groups; by project officers and engineers assigned to follow up individual projects; and by the complete system operated by the Ordnance Technical Intelligence Branch for collection and dissemination of all relevant items of foreign and domestic technical intelligence. Another way in which coordination is effected is through conferences of selected groups. For example, at least once a month the Navy Bureau of Ordnance and the Army Ordnance Department review in joint conference all their research and development projects. Pertinent technical reports are mutually exchanged, and many projects are pursued jointly. Likewise, the liaison with NDRC (National Defense Research Committee) is strengthened by frequent conferences and interchange of technical reports between the various divisions of the National Defense Research Committee and the Ordnance Department Research and Development Service. General coordination with the resources of science, technology, and industry is effected through close and continuous contact of the Research and Development Service with special consultants, scientific and industrial advisers, and with special advisory and working committees such as those established for this purpose by national engineering and technical societies. To illustrate, the SAE-Ordnance Advisory Committee, in existence for many years, has rendered advice and assistance of inestimable value to the Ordnance Department in the development of automotive materiel.

Of special note also are the Ferrous and Non-Ferrous Ordnance Metallurgical Advisory Boards, whose membership includes outstanding metallurgists in their respective fields. These Boards meet from time to time, or upon call of this Service, to assist on metallurgical problems, especially with respect to specifications of materials. The work of the Subcommittees established under the Ferrous Board early in this war, which are described elsewhere in this issue in the article on Metallurgical Research, prepared by Lt. Colonel N. A. Matthews of Watertown Arsenal, was vital in the development of armor, armor piercing projectiles, gun forgings, and welding of tank armor for our armed forces. In this manner, the best talent and the best facilities of science and industry were brought to bear on urgent Ordnance problems.

General coordination of Ordnance research and development with the needs of our using Arms and Services and of our Allies is effected through the Ordnance Technical Committee, described in General Barnes' article. No Ordnance item ever receives approval for quantity manufacture and issue until intensive research and development have been followed by performance tests at the Ordnance proving grounds. Reports of these tests may contain certain recommendations for acceptance or rejection, or for modification. Before it is recommended for standardization, the item is usually subjected by the Service Board of the using Arm to exhaustive field test, simulating

combat conditions. If the item performs to the satisfaction of the Ordnance Department, and meets requirements of the using Arm, it is immediately recommended by the Ordnance Technical Committee for final standardization or for limited procurement to meet a special military requirement.

Military channels of command and liaison afford close support of higher staff echelons of Army, Navy, and other government agencies, and close contact and cooperation between corresponding working echelons of those organizations. Articles by General Borden and Colonel Osborne in the April, 1945 issue of the *Journal of Applied Physics* describe higher echelon aspects of Army research and development.

Much of the detailed work involved in coordinating and indicating the applications of research to the development of Ordnance materiel is performed by the Research and Materials Division of the Research and Development Service. The Chief of this Division represents the Ordnance Department as Assistant to the War Department Liaison Officer for the National Defense Research Committee, and as the principal contact of the Department with research activities in general. Work of the five branches of this Division is here briefly described.

The Research Coordinating Branch exercises general coordinating supervision over the programs and activities of the eight Ordnance laboratories which are maintained at Aberdeen Proving Ground, and at the manufacturing arsenals, each laboratory being devoted to keeping alive and in vigorous growth certain special branches of the Ordnance art. Some of the activities in several of these laboratories are described in other articles in this issue of the Journal. This Branch supervises detailed Ordnance liaison with the National Defense Research Committee and other scientific and technical bodies. It is to be noted that the Ordnance Department has sponsored with National Defense Research Committee during this emergency over 225 projects. Of these, 180 have been completed or terminated and 48 remain active at the present time. This Branch administers the technical processing of inventions for war use submitted by the National Inventors Council and others to the Ordnance Department. Since Pearl Harbor, more than 2000 inventions or suggestions have been received from the National Inventors Council and considered by Ordnance. In this connection, the National Inventors Council has taken a tremendous burden from the Ordnance Department by screening through its technical staff the vast stream of suggestions and inventions received from all sources, and referring to Ordnance only those which relate to Ordnance work. This Branch also maintains representation on the Army-Navy Patents Advisory Board and on technical committees of other Technical Services.

The Technical Intelligence Branch is engaged in the collection, analysis, evaluation, editing, and dissemination of technical intelligence bearing upon Ordnance research and development activities. This Branch supervises the work of the Ordnance Technical Intelligence teams who have been operating with the armies in the combat theaters for several years collecting enemy materiel for shipment to the Aberdeen Proving Ground for detailed examination and test. An exceptionally complete collection of enemy materiel is maintained continually under study and test. Special developments and trends are brought to the immediate attention of those concerned. Special reports and technical assistance are rendered to the War Department and to other agencies engaged in the war effort. A complete system of collection, editing, and distribution of current reports and items of technical Ordnance information is maintained by this Branch between the Research and Development Service and interested agencies throughout our own and Allied governments and scientific and technical organizations.

During the past year, the activities of Ordnance Technical Intelligence have been considerably expanded incident to the occupation by our armed forces of territory formerly controlled by the Germans. This work has been intensified since our armies crossed the Rhine. A competent staff of Ordnance technical investigators, including outstanding representatives from science and industry, have been in Germany with the armies since the occupation to insure that all possible technical data and information of use to Ordnance on German facilities, research, and development will be obtained and utilized.

The Ballistic Branch supervises the preparation of firing and bombing tables and special ballistic data for the armed forces and advises on all ballistic characteristics affecting Ordnance design. It formulates and supervises programs of ballistic research and the development of improved ballistic instrumentation and computation. It coordinates the activities of the Ballistic Research Laboratory at the Aberdeen Proving

Ground with related activities of other agencies. This laboratory, which includes the new supersonic wind tunnel for the aerodynamic study of projectiles, is exceptionally well equipped for its work and includes in its advisory and working staffs many of the foremost scientists in this country. An article on some recent developments of this laboratory is included elsewhere in this issue.

The Materials Branch is concerned primarily with Ordnance aspects of materials and processes, on which the Branch engages in direct research and development. In this connection, it maintains collaboration, liaison, and representation with other agencies and supervises certain activities within the Ordnance Department with which it is directly concerned. A most important function of the Branch is the safeguarding, through specifications, of the quality of Ordnance materiel and materials. Specifications for all Ordnance materials (with a few specific exceptions) are prepared and formulated in this Branch. It also assists in the preparation of specifications for finished materiel. This work involves a considerable amount of materials engineering, including planning, supervision, and coordination of the work conducted by various other agencies in this field. A continuous and intensive study is made of materials and methods best adapted to resist corrosion and tropical deterioration due to fungus and humidity. Studies are also made of captured enemy materials, and foreign technical intelligence is analyzed and applied wherever useful.

Outstanding examples of the work of this Branch are found in the steady improvement of the properties of gun, armor, and projectile steels; in the increasing substitution of welded high tensile strength steel plate for the heavy forgings and castings formerly specified in the construction of artillery mounts and combat vehicles; and in the increasing Ordnance use of lightweight high strength alloys and of plastics. Substantial improvements have been made in the quality of cartridge metal. The Branch also has assisted in the Ordnance program for the development and utilization of synthetic rubber. During the period of critical shortages, by intensive study of actual Ordnance needs and the available resources, this Branch rendered very great assistance in the conservation of strategic materials, and conservation is still part of its work. An article by Colonel John H. Frye, which appears elsewhere in this issue, gives additional data on research, development, and applications of materials for Ordnance purposes.

The Fuels and Lubricants Branch was brought into being by the need of intensive and coordinated work in a special field that is vital to Ordnance. Fuels and lubricants are the life blood of the modern automotive military equipment, which demands optimum performance under all conditions of service. Recoil oils are essential to artillery, and special lubricants to fire control instruments. Special compounds are needed for hydraulic brake fluids, rust prevention, and cleaning and preserving materiel.

Under the planning, direction, and supervision of the Fuels and Lubricants Branch, a vast amount of successful work has been done, much of it by working groups organized jointly by this Branch and the Coordinating Research Council. The initially very large number of different fuels and lubricants has been greatly reduced and each type that has been retained has been greatly improved in performance and storage characteristics. Ordnance needs for vast quantities, rapidly supplied, have been carefully correlated with the ability of industry to meet these needs; and by mutual adjustments the flow of satisfactory materials has been maintained with quality constantly improving. A single type of recoil oil has been developed which meets practically all conditions of service and replaces several different types previously thought necessary. Each Ordnance fuel and lubricant now in use can be stored and will operate successfully over a wide range of climatic and other conditions which affect storage and performance. Current changes in the military characteristics demanded and in industrial practices are successfully studied and matched. An article by Lt. Colonel R. E. Jeffries, which appears elsewhere in this issue, gives additional data on research, development, and application of fuels and lubricants for Ordnance purposes.

Research on many of the materials mentioned is influenced by specific tests to which Ordnance materiel is subjected. These cover operations under the most adverse conditions of climate and terrain from the mud and humidity of jungle tropics and the sand, dust, and heat of the desert, to the extreme cold, snow, and ice of the arctic. Materials and materiel must meet these most exacting demands and still perform satisfactorily.

In the development of new and improved Ordnance materiel every effort is made to anticipate and to avoid difficulties which might later be encountered in manufacture, transportation,

storage, and use and to minimize such difficulties as cannot be altogether avoided. In this connection, research is constantly invoked and successfully applied.

Details cannot be given of the new materiel and new methods of warfare which have resulted from the application of intensive research to the problems of Ordnance. The vast amount of research and development work accomplished is indicated by the fact that practically all of the major items of Ordnance equipment in existence at the commencement of this war have been replaced by entirely new items, or have been radically redesigned. The excellence of our present armament is evidence of the thorough coordination of research and of the effective application of the results of this research to actual development.

This war has demonstrated conclusively that for national security there is necessary the closest possible working partnership between science, industry, and the Ordnance Department. Each must be kept constantly informed of the needs, capabilities, and limitations of the others. This partnership has wrought miracles in the research, development, and production of Ordnance materiel during this emergency. Without this partnership, and the effective cooperation of all agencies concerned, the great responsibility of the Research and Development Service could not have been discharged. This partnership should be continued in peace as well as in war. Constructive planning is now under way to this end.

AMMUNITION RESEARCH AND DEVELOPMENT

By Colonel I. A. Luke
Chief, Ammunition Development Division

THE continuous mission, both in peace and in war, of the Ammunition Development Division of the Ordnance Department is to execute research and experimental development on items of ammunition and their components up to the point of standardization for military use by the armed forces of the nation.

Such research and development rests upon the structure of applied physics, chemistry, and mathematics. Approved designs must, of course, meet all the production requirements for these modern times and conditions. Therefore, any design of an item must be engineered for mass production and such components of an item as a high explosive must be capable of safe production and use under all the specified conditions. Raw materials used in ammunition must be readily available for quantity production.

Research and development of ammunition embraces not only specific ammunition items such as all calibers of artillery ammunition, bombs of all types, grenades, mines, pyrotechnics, and demolition charges, but also special explosives, propellant powders, paints, etc., together with their raw materials. Technical research in materials is of course similar to that going on in industry, and is for the purpose of freezing specifications between such upper and lower limits that any selected substance can be employed satisfactorily when used in the completed item.

The initiation of a development project for an item may arise from a number of sources. In many cases it is the result of the integrated forward thinking of Ordnance men; in other cases as a requirement for an item found desirable or necessary by the using military forces to meet an actual or anticipated tactical or strategic situation in warfare. It may also be based on intelligence information from any source deemed to be reliable. The need for new weapons to maintain parity or superiority over any possible enemy is ever present. Hundreds of ammunition items have been brought through the development stages to standard status and introduced on the battlefields in this war. Many of these have been entirely new weapons; others have been improved weapons which rendered the previous ones obsolescent.

Briefly, the steps in the research and development of an ammunition item are as follows:

a. As soon as preliminary study indicates the feasibility of carrying through successfully a development for a desirable or requested item, a development project is formally initiated by Ordnance Technical Committee action. This action is approved by all agencies concerned in the ultimate outcome.

b. Development proceeds by placing Research and Development contracts with commercial concerns, by directive to Ordnance Arsenals, by request to other government agencies such as the Navy Department, the National Defense Research Committee, Office of Scientific Research and Development, the National Bureau of Standards, etc., to the end that sufficient units of an item meeting the stated military characteristics may be delivered to the proving ground for

engineering tests. This stage is completed when the requirements are met.

c. Quantities of the new item are tested under all necessary conditions by the various Service Boards representing the using troops to determine whether the new item meets the military requirements in all respects, and whether or not further extended service tests by the troops is necessary before standardization of the item is recommended.

d. Standardization of the item, either in full or as a substitute.

The normal course of a development item of ammunition requires from a few weeks to many months, depending on the type and complexity of the item.

Ammunition may be said to be the heart of the capacity to make war. And why is this so? An examination of the matter reveals that the infantryman moves forward in proportion to the superiority of his fire power from rifle, machine gun, mortars, bazooka, or grenades and as supported by the fire power of artillery and air forces. The tankman is superior on the battlefield to the extent that his ammunition knocks out his adversary by either high explosive shell or armor piercing shot. The Air Forces' ammunition in the form of bombs, shell, etc., determines tactical and strategical superiority by its terminal effects on the enemy targets. Items of ammunition may be hand placed, as in the case of demolition charges, land mines, etc., thrown by hand as exemplified by high explosive, smoke, or other types of grenades, projected from rifle launchers in the form of high explosive, smoke, or anti-tank grenades, fired from guns, howitzers, and mortars in the types of high explosive shell, armor piercing shot, illuminating shell, etc., or dropped from aircraft in the types of fragmentation, demolition, armor piercing, or chemical bombs.

For centuries, guns and the ammunition fired from them were limited by the fact that the burning of the black powder propellant used as the charge could not be controlled. Black powder, consisting of an intimate mixture of potassium (or sodium) nitrate, charcoal, and sulphur in the approximate percentages of 75, 15, 10, was the only propellant known from the latter 13th century until the latter half of the 19th century. Guns were made of wrought iron, cast iron, or bronze until the theory of built-up guns and improved steels produced better designs in the last 20 years of the 19th century.

The fundamental advances in chemistry which led to smokeless powder, the burning of which could be controlled in a gun chamber, were:

a. The discovery that a base like cellulose could be nitrated by treatment in a mixture of sulphuric and nitric acids and thereby become an explosive substance—nitrocellulose; and

b. That by a proper processing of this nitrocellulose in a solvent of ether and alcohol, a colloid resulted which, when pressed through dies in certain granular forms and dried, would, upon burning, evolve heat and gases in a regular manner.

As soon as the laws of burning became known, gun strengths and the energy of the propellent powder were so correlated as to produce a weapon which would withstand the developed pressures at all points along the bore.

The development of ammunition rests upon combining metals and explosives in such a manner as to meet the military characteristics demanded in each case. It is therefore desirable to discuss certain fundamental facts which form the basis for such development.

An explosive substance may be a mixture of certain ingredients none of which are explosive in themselves (such as black powder), a chemical compound, such as TNT, or a combination of mixtures and compounds. The effects from an explosive depend on (1) the heat given off in calories per unit mass, (2) the quantity of gas evolved in cubic centimeters per unit mass, and (3) the rapidity of the reaction, which is measured by the linear rate at which the explosive reaction takes place. An explosive reaction liberates heat and is therefore exothermal. The transformation is one of complete decomposition; hence the system presents extreme sensitiveness. The "potential" of an explosive may be defined as the total work that can be performed by the gas resulting from the explosion, when the gas is expanded adiabatically from its original volume to normal atmospheric temperature and pressure.

Building up such potential in any substance is accomplished by the process of nitration. A compound like cellulose, which is a very complex chain structure of the form $(C_6H_{10}O_5)$ taken four times, may be nitrated to produce a series of cellulose-nitrates extending from cellulose tetranitrate $C_{24}H_{36}O_{20}(NO_2)_4$ to cellulose-dodekanitrate $C_{24}H_{28}O_{20}(NO_2)_{12}$ and with nitrogen contents from 6.77 to 14.14 percent. The average nitrogen content of the nitrocellulose in single base propellants is approximately 13.15 per-

cent. Similarly aromatic compounds like toluene, $C_6H_5(CH_3)$, may be nitrated to trinitrotoluene (TNT) by replacing three H atoms by NO_2 groups and the substance then has the formula $C_6H_2(CH_3)(NO_2)_3$. Tremendous potential energies are thus brought into the molecule in the form of NO_2 groups or radicals, and a system is provided which is sensitive to heat or shock in the proper amount necessary to start the explosive reaction which results in a recombination of the constituent parts. In a radical such as NO or NO_2, etc., the oxygen atom separates from the nitrogen atom and combines with carbon or hydrogen or other oxidizable atoms. It is interesting that nitrogen, which is trapped in a chemical compound only by the expenditure of much energy, goes back toward its free state in nature with such a burst of speed once the bonds are snapped. The ruined cities of Europe are mute testimony of this latter phenomenon.

One more point in connection with an explosive reaction should be mentioned. When an explosion occurs at some point in an explosive mixture or compound, an explosive wave is set up as the explosive substance decomposes. This single wave motion is produced by a certain concordance between the physical and chemical impulses resulting from the matter undergoing transformation. The wave is propagated from layer to layer throughout the mass in accordance with successive impacts of the gaseous molecules which have been brought to a state of intense vibration by the heat given off in the reactions. The explosive wave is, therefore, a moving system which receives its enormous energy from the chemical reactions in the explosive, the ultimate result of which is the evolution of heat and gases.

The measurement of this rate of explosion or detonation in terms of meters per second is a useful yardstick to indicate the relative ranking of the explosive as "low" or "high." Propellants are usually low explosives; such explosives as mercury fulminate, lead azide, TNT, etc., are high explosives.

Since, therefore, the propellant or high explosive is a certain volume and weight of material containing enormous energy ready to be liberated, it is paramount that such liberation occur at a specific time only; otherwise disaster will result. The remarkable fact about the technology of ammunition is that it has been found possible to control these explosives during manufacture and loading into metal or other containers, to

FIG. 1. 81-mm mortar shell.

make them remain *in status quo* in storage and transportation, and then withstand the forces encountered in firing from weapons or release from airplanes—and then secure the ultimate results, called "terminal ballistics" at the target. This is accomplished by research and development of all components that make up what is called "the explosive train."

The various parts of the explosive train are developed to accomplish the final liberation of energy in the explosive to meet the military characteristics desired. In some units more than one train is required. An example will illustrate how a typical round functions, and how the explosive train principles are utilized to achieve the desired results.

In a complete round of ammunition of 81-mm mortar ammunition, designated "Shell, HE, M43A1, with Fuze, PD, M52, 81-mm mortar," there are two explosive trains required (Fig. 1):

(1) A train which will safely propel the entire round out of the mortar. The elements of this train are: a primer which upon striking a firing pin embedded in the bottom of the mortar

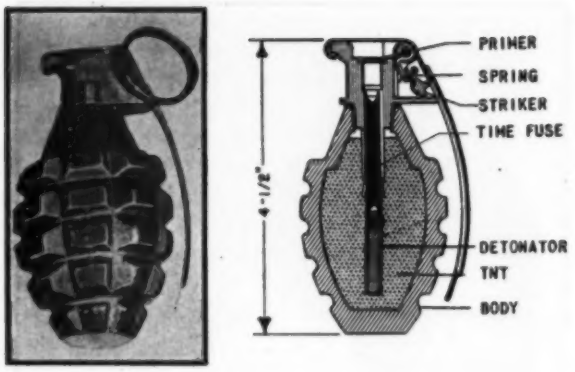

FIG. 2 and 2a. Hand grenade.

causes the primer mixture to fire and deliver hot gases into the ignition cartridge, which contains sufficient propellant, if used alone, to raise the pressure in the mortar behind the projectile to produce a muzzle velocity of 235 feet per second and reach a range of 541 yards. The pressure builds up in the ignition cartridge, and the hot gases blow through the holes in the tail of the mortar shell, and ignite from 1 to 5 increments of double base propellant in the form of sheets located in the spaces between the fins. The number of these increments used depends upon the range desired. The maximum number of increments would reach a maximum range of 2963 yards. This train is "low" explosive in character.

(2) A train, high explosive in its functioning, starts its course upon impact at the target. The superquick fuze, M52, is the first element of the explosive train. During firing at the mortar the fuze is caused to go from a "safe" condition to an "armed" condition by utilizing the force of "setback" to cause a proper size pin to go rearward and unlock a pin which flies free after emergence from the mortar. This leaves the striker head of the fuze free to strike a detonator of lead azide upon impact. A detonator usually consists of lead azide-tetryl charges or mercury fulminate pressed in a metal cylinder, the whole unit being held securely in a metal housing. Such a detonator or initiator is the first element of the HE train. A detonator has the characteristic of detonating under critical conditions by impact, friction or heat. Further the "blow" delivered at the boundary of the detonator can be made amply sufficient to detonate with characteristic high rate the next explosive unit called a "booster." This unit consists of Tetryl (Tri Nitro Phenyl Methyl Nitramine). The purpose of the booster is to assure a rate of detonation on its outside boundary high enough to produce the characteristic rate of detonation of the main bursting charge or filler which is ultimately to do the damage. Sufficient lead azide is able to detonate tetryl with high order (rate of detonation 7000 meters per second) and such rate is about 500 meters per second higher than that of the cast TNT bursting charge of the shell.

The tremendous kinetic energy resulting from the detonation of the high explosive causes the metal shell case to fragment, with resulting fragment velocities of 3000 to 4000 feet per second and a concurrent blast effect from the gases traveling outward from the burst center.

Although it is not possible at this time to discuss many items of ammunition developed during the war, it is possible to mention sufficient examples to illustrate how projects in ammunition research and development result in new weapons for our troops.

Early in the war, our troops found that, when fighting in the dense jungles at night, the then standard hand grenade Mk II (TNT) with fuze M6A4C (see Fig. 2) gave such a sharp primer report and flash on initiation of the black powder train and smoke when thrown, that Jap snipers in trees or elsewhere were able to shoot at the thrower.

Research and development brought to standardization the grenade, hand, fragmentation, Mk II (TNT) with Fuze, Grenade, Hand, M204. This fuze is smokeless, sparkless, and noiseless. As the grenade leaves the hand, the safety lever releases the striker which ignites the primer, the first element in the explosive train. The primer immediately ignites the next element in the train—a 4.0–5.0 second time fuze—which in turn initiates a 13½ PETN detonator, and this detonates the main explosive filling of TNT. The development of the fuze powder with such characteristics and its successful adaptation in fuze design was an outstanding scientific accomplishment and will save many American lives.

The definite trend in higher speeds and velocities in all lines of endeavor and in most technologies has been and will be very important in the field of ammunition. Whereas in World War I, for example, one of the most powerful mobile field artillery weapons, the 155-mm GPF gun, fired a 95-lb. high explosive projectile with a muzzle velocity of 2410 feet per second and reached a maximum range of 17,500 yards, this

present war's 155-mm gun, M1 (called the "Long Tom"), fires the same weight of projectile, but improved in ballistic shape, at a muzzle velocity of 2800 feet per second to a maximum range of 25,715 yards. The development of ammunition to reach longer ranges has been carried out in practically all weapons. The necessity of meeting the higher and higher linear and angular accelerations and velocities, with resulting centrifugal forces, etc., in the bore of the gun, has challenged the technical ingenuities of the developing groups. With such high velocities the kinetic energy of the propellent gases reaches such heights that they are still exerting considerable pressure on the base of the projectile as it emerges from the bore and the gases are incandescent and flash. The almost universal requirement in battle for "no flash" and "no smoke," without reduction in range, has been stated as the development goal.

In the 155-mm gun, M1, and others of the same caliber, it has been found possible to control the flash of these powerful weapons by means of the Flash Reducer, M1. The Reducer consists of two cotton strips linked together with silk strings. Each strip contains three channels filled with chemical substances. The ensemble is tied around the propelling charge and fired when no flash is desired. Considerable smoke results when the Flash Reducer is used, but for night firing particularly, a real advantage to our troops is obtained by its use (Figs. 3 and 3a).

In the high velocity tank and anti-tank guns, which have played such an important role in the present war and will probably continue to do so in the future, the question of flash and smoke is very important. The intense flash of a normal standard propellant blinds the gunner. Too much smoke from a flashless round makes it difficult to keep the target constantly in view. In 76-mm tank guns, the use of a very long 19" primer inserted into the cartridge case permitted forward ignition and inflammation of the propelling charge with such completeness and uniformity from round to round that the gases were below the ignition point at the muzzle. Also there was sufficient lessening of smoke so that the gunner could keep the enemy target in view at all times In a tank duel, the speed of firing accurate shots is paramount.

In the future the attainment of flashless, smokeless propellant without loss of velocity is a development goal for all weapons.

Since tanks have played an important role in the present war, some information regarding the ammunition developed for the guns of these weapons should be stated. One of the principal missions of a tank, although perhaps not the most important, is to destroy an enemy tank. The principal round fired is the standard Armor Piercing Shot to penetrate the enemy tanks' armor or other resistant material. For the 90-mm M3 gun, for example, the standard projectile, designated M82, complete with cap and windshield, weighs 24.11 lb. and has a base detonating fuze which, with its delay element and booster, detonates a bursting charge of explosive "D" after penetration of the armor. A tracer element permits the gunner to follow the path of the projectile to the target.

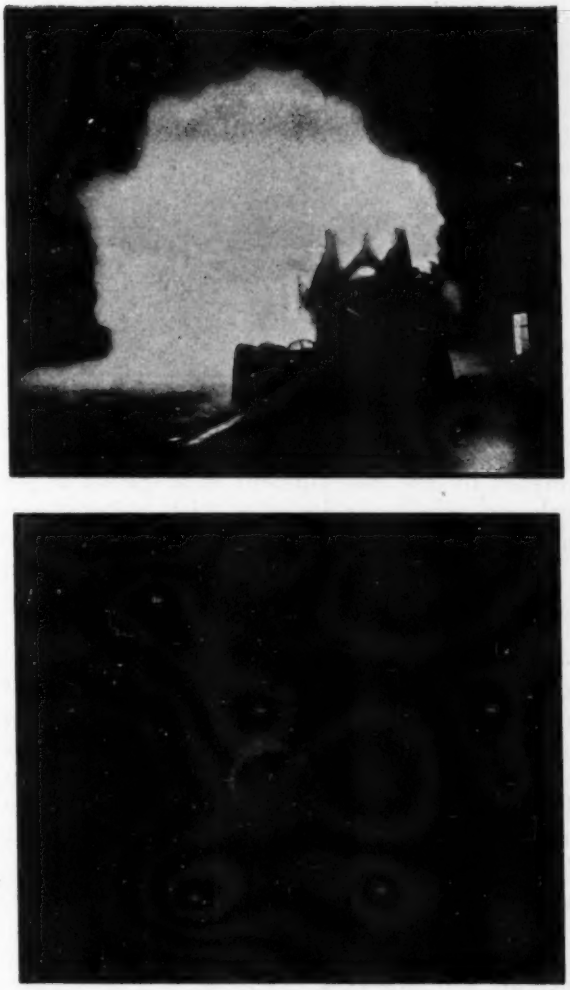

FIG. 3 and 3a. 155-mm gun, M1, firing without and with Flash Reducer.

Penetration of more inches of armor than is possible by the regular standard shot was accom-

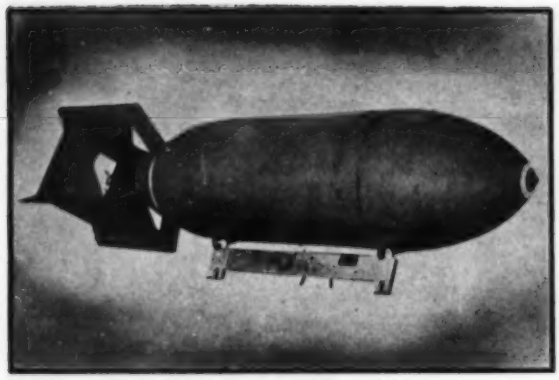

FIG. 4. 2000-lb. bomb, M103.

plished by the development of a special hyper velocity armor piercing shot with tracer designated "shot, fixed, H.V. AP-T 90-mm, M304."

This special shot consists of an 8-lb tungsten carbide core held in a base of steel, with an aluminum body and with a nose plug and windshield. The steel base is tracer loaded. The assembled shot weighs 16.7 lb. Fired in the M3 gun at 2000 yds. the extreme horizontal dispersion of a group of shots on a vertical target was 17 inches and the extreme vertical dispersion 30 inches. The time of flight of the projectile from the muzzle of the gun to the target at 2000 yards is 2.08 seconds. Time of flight, accuracy, and penetrating ability of the shot are characteristics that determine gun superiority.

The development of the hypervelocity armor piercing shot for tank destroyer and tank guns has been carried on during the present war. In the future, the trends of development point toward shot for larger caliber weapons with higher velocities and improved accuracy. These trends together with the demands for the smokeless, flashless propellants previously referred to present a challenge to the scientific men of the country for better and better solutions and attainments. There can be no relaxation in effort.

The semi-armor piercing bomb, 2000-lb. M103, illustrates the manner in which a requirement for an item of aircraft ammunition has been met by the Ammunition Development Division. The military characteristics for this bomb were that it would penetrate reinforced concrete pillboxes and other targets of high resistance and that after such penetration would have an explosive effectiveness equivalent to that of the 1000-lb. General Purpose Bomb AN-M65A1.

The bomb which was developed is shown in Fig. 4. It is 90 inches long, $18\frac{5}{8}$ inches in diameter and has a minimum wall thickness of $1\frac{5}{16}$ inches. Its metal weight is 1450 lb. and it carries a heavy charge of high explosive. Tests indicate that at a terminal velocity of 1000 feet per second this bomb will penetrate almost any concrete structure and perform with equal efficiency against heavy armor plate.

A delay element is incorporated in the explosive train to permit penetration of the target before the bomb detonates. The extremely heavy stresses set up by impact with the target require that the bomb body must be strong enough to resist deformation and that the high explosive charge must not detonate on "set forward" caused by the shock of impact. It is readily seen that in a low altitude attack by a high speed airplane against a resistant target the proper delay in detonation of the bomb after impact is one of the margins of safety which enable the pilot of the bomber to make a safe getaway.

Space does not permit further examples of specific ammunition items newly developed or improved during this war. The items number dozens in each general category. An average load of approximately three hundred major research and development projects looking toward the ultimate standardization of new or improved items of ammunition or components thereof has been carried during the present war. It cannot be too strongly emphasized that research and development along sound lines must be supported to the utmost by the nation as a matter of policy and by sufficient funds and specifically by all scientific and technical groups both in and out of government to the end that our troops may continually be supplied in war with the best possible weapons.

Many trends in future development are now in evidence. Others will constantly appear. The advent of the airplane which made possible third-dimensional war has called for the utmost in firepower for aircraft in the form of general purpose high explosive bombs and their fuzes, fragmentation, chemical, incendiary, and special bombs; semi-armor piercing and armor piercing bombs; signals and flares; and aircraft cannon and machine gun ammunition. The extreme speeds and altitudes at which future aircraft will fly indicate at once that research and development of these items must ever be at the fore. The attainment of enormous ranges by ground-fired projectiles such as the robot and similar types is mentioned to illustrate and emphasize

the fact that there can be no complacency in the matter of having the best possible weapons on hand when trouble starts. It is a safe estimate that in future there will be no time delay possible to permit research and development after an aggressor strikes.

The weapons for our troops to meet any threat to the nation will be the result of continuous research and development fully supported by all groups, both in and out of government. Such support and cooperation by every concerned agency of science, industry, and government will assure that the responsibilities of the Ammunition Development Division of the Research and Development Service may be met.

ARTILLERY MATERIEL RESEARCH AND DEVELOPMENT

By Colonel W. R. Gerhardt
Chief, Artillery Development Division

ORDNANCE research and development have followed a pattern characterized by periods of great activity during wartime separated by years of seeming inactivity during peacetime. This pattern has been set by the amount of funds appropriated by the Congress. That research and development were not inactive during the interval between World Wars I and II will be evident from a brief review of some of the accomplishments of that period.

Prior to World War I, the funds available to support research and development were so limited that we entered that war in a state of unpreparedness both as to types of materiel to be produced and facilities for production. Fortunately, our allies were able to supply our deficiencies, and we emerged from that war with a large quantity of artillery materiel which was stored and maintained as a reserve for future conflicts. Although during the subsequent years of peace this materiel gradually became obsolete, it still served as a restraining influence on research and development, for it appeared uneconomical to appropriate funds for research, development, and trial production of new materiel while our storehouses were full of weapons being maintained for the next war.

In 1918 a board of officers, commonly referred to as the Caliber Board, was charged by the War Department to make a study of the armament, calibers, and types of materiel, kinds, and proportion of ammunition, and methods of transport of artillery to be assigned to a Field Army. In its report, approved in 1919, the Board recommended development of nine classes of wheeled artillery weapons, with corresponding self-propelled versions in most of these classes. The recommendations of the Caliber Board were sound and farsighted. The characteristics specified in the weapons were limited to those necessary to the fulfillment of tactical missions envisioned and avoided detailed design specifications that are soon outmoded by new developments.

The development of many of the artillery weapons used so effectively by our armies in World War II emanated from the types recommended by the Caliber Board. Included are the 4.5-inch, 155-mm, and 8-inch guns; the 105-mm, 8-inch, and 240-mm howitzers; the 75-mm pack howitzer; the 120-mm antiaircraft gun; and many self-propelled versions of these weapons. In addition, development of many items of railway artillery, artillery prime movers, motor transport, and related artillery equipment were completed to meet the requirement set forth in the report of the Board.

During the interval between World Wars I and II, funds provided for research and development were inadequate. It was possible to work only on a few projects at a time. Many important projects, involving expenditure of considerable funds, such as fire control systems for anti-aircraft guns, had to be separated into phases and carried out on the installment plan over periods of several years. Both for reasons of economy and the necessity of keeping trained personnel and facilities in readiness for wartime expansion, most research was done at arsenal laboratories, and most design and engineering was performed in engineering sections of the Ordnance Office in Washington and of arsenals. With but a few exceptions, research, development, and engineering organizations in industry could not be interested in peacetime Ordnance work.

Nevertheless, during the lean years preceding World War II, a great deal was accomplished in the field of artillery research and development. This is borne out by the fact that, instead of borrowing from our allies as we did in World War I, we were able not only to equip our own rapidly expanding army with modern materiel but to supply our allies as well. Some of the accomplishments were in the forms of completed development projects, with pilot models built, tested, and approved, and with drawings and specifications ready for procurement. Other accomplishments were less evident, consisting of

FIG. 1. 8-inch gun.

accumulated training, knowledge, and experience in specialized lines on the part of Ordnance officers and engineers that enabled them, when our industry entered the war, to guide and direct its efforts in channels that produced the desired results in the minimum time.

Prior to the attack on Pearl Harbor, development had been completed and weapons standardized to meet all the requirements of the Caliber Board for wheeled artillery, except for the 120-mm anti-aircraft and 8-inch field guns (Fig. 1), and the 240-mm field howitzer (Fig. 2). Because of the cost of these heavy weapons and limitations on funds, their development was laid aside until war became imminent. However, their development was completed during the early part of the war and before requirements for them were fully recognized. Among the weapons developed prior to our entry into the war were 60-mm (see Fig. 3) and 81-mm mortars; the 37-mm antitank gun; 37-mm, 40-mm, 3-inch, and 90-mm antiaircraft guns; 75-mm pack and field howitzers; 105-mm, 155-mm, and 8-inch field howitzers; 75-mm, 4.5-inch, and 155-mm field guns; and all types of seacoast and railway weapons required in our harbor defenses.

Thus, when we entered the war, modern designs of weapons were available in all classes except three of the larger calibers. This does not mean that all these weapons were ready for production. With but few exceptions, the designs had not been reviewed and tested for adaptability to production in quantity because of insufficient funds. The first fruitful recognition of the necessity of adapting designs to quantity production came in 1938 with the appropriation by the Congress of funds for educational orders. But the large variety of Ordnance equipment and the limited funds appropriated did not permit more than a sampling coverage with a few selected items. Thus, again our preparedness for a major war was inadequate. That this situation did not result in disaster is partly because of our geographical location and the protection of our allies, but it was overcome largely through the cooperation of industry in the formulation and operation of the Industry-Ordnance Team for development, production, and supply.

The factors that determine the types and characteristics of weapons required for a war are largely guesses until the enemy and theaters of operations are known. Prior to the attack on Pearl Harbor, the extent of our participation in World War II was not sufficiently definite to indicate that we would be fighting simultaneously in deserts, arctic regions, and tropical jungles. Consequently, with our entry into the war there began a period of intense development wherein time has been the controlling element. The established objectives were to provide our troops with the best weapons for the conditions under which they were to operate, and at the same time to maintain weapon superiority over our enemies in all theaters. Because of the long period between the inception of a new artillery weapon and its supply to troops, this objective requires that weapon development look far beyond current operations and tactical requirements, and anticipate future needs.

The importance of the time element in the development of new weapons during wartime, especially against an enemy of scientific and productive ability, could not be neglected. Between ourselves and the Germans particularly there was a continual race to put superior artillery firepower on the battlefields. As a result, our wartime developments include many improvisations and expedients that will require refinements and further developments as time permits. A great disadvantage of longer supply lines had to be offset. A few examples of these rapid wartime developments will be given.

During the North African Campaign there was noted a trend in German practice to increase the

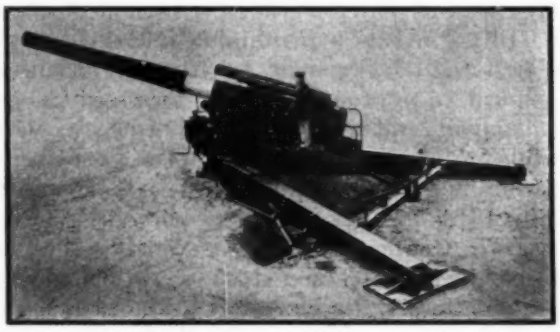

FIG. 2. 240-mm howitzer.

armor and velocity of tank guns pointing to an early outmatching of our 75-mm gun. To meet this challenge a high velocity tank gun of 76.2-mm caliber, outmatching the German 75-mm tank gun, was developed and placed in production in record time. Later, with the adoption of a defensive role, the Germans sacrificed mobility to secure greater armor protection and firepower. The high velocity 90-mm tank gun was developed to maintain our superiority. Concurrently, wheeled antitank guns in 3-inch and 90-mm calibers were developed and standardized.

The advent of large scale airborne operations created requirements for weapons that could be transported readily in airplanes and gliders. To meet these requirements modified types of 40-mm and quadruple caliber .50 anti-aircraft weapons were developed. The 75-mm pack howitzer was modified and paracrates developed to permit air drops. A special light weight 105-mm howitzer was developed with this use in view, but it was subsequently decided that its employment should be with ground troops.

Early experiences in the Pacific areas indicated a need for special types of weapons for use in jungle warfare. Many weapons were developed to meet this need and were flown by airplane to those areas for trial. Artillery weapons developed for this purpose included a light-weight 37-mm gun suitable for manpack, special types of 60-mm and 81-mm mortars, and larger mortars.

The frequent occurrence of amphibious operations, particularly against shores where the ability to beach landing craft was unpredictable, necessitated the rapid development of methods and materials whereby weapons could be protected against the corrosive action of salt water during the landings. Special waterproofing kits, readily applied in the field, were provided for all artillery materiel to be used in these operations.

Concurrently, with the development of new weapons to meet new requirements arising from changes in warfare, extensive development was carried on with the objective of improving existing materiel to make it more effective in intended roles and to incorporate improvements found desirable from battlefield experience. In some cases this resulted in a complete redesign of the material; in others, modification or substitution of new components was sufficient to achieve the desired results.

Probably more than in any other field, improvements and innovations have been made in fire control methods and equipment. These are

FIG. 3. 60-mm mortar.

the logical results of increased speeds and mobility and decreased vulnerability of equipment used in battle. They have been aided by rapid progress in scientific fields, particularly electronics. Further, and of great importance, is the fact that continued investigation and accumulated experience during recent years have resulted in the ability to provide in the more complex mechanisms and components of fire control equipment the reliability and ruggedness required for field use.

For controlling the fire of anti-aircraft guns, fire control systems have been developed in which the tracking of the target will result automatically in the positioning of the gun and setting of the fuse so that the projectile will burst at the position in which it is predicted that the target will be at that future time. Similar systems have been developed for use against ships by seacoast artillery. For smaller caliber weapons less complex computing sights, by means of which the proper lead angles are given automatically to the gun, have been developed for mounting on the weapon. Telescopes, sights, binoculars, range finders, and similar classes of fire control equipment have been improved, both mechanically and optically. The increased importance of night fighting has necessitated the provision of reticle illumination and lighting devices for gun sights. Improved quality and types of optical glass and plastic substitutes, coatings to improve light transmission and protect surfaces, and better sealing and use of desiccants have resulted in better optical performance and extended the serviceability of instruments under all conditions.

World War II has brought forth, more than

any war in the past, new scientific achievements that will affect the conduct of future wars and the weapons with which they will be fought. The potential value of American industry has been clearly demonstrated in this war. It must be expected that any future attack planned against the United States will take full cognizance of our industrial potentialities and will include provisions for means of their destruction. It must be anticipated that further developments in airplanes, V-2 bombs, and new weapons may result in initial attacks directed against Chicago and Detroit instead of Pearl Harbor. Through continuing research and development we must evaluate such possibilities and have available means of counteracting them, but preferably we should be far enough ahead of any possible enemies to discourage any thoughts of attack. It has been demonstrated beyond dispute that the cost of adequate preparedness is the cheapest form of insurance.

Further development of artillery materiel should include a complete and unbiased evaluation, based upon all conceivable conditions of warfare, of all our weapons and developments to insure that we have a complete coverage as to types of weapons. We should not hesitate to develop and standardize types of weapons to meet requirements that seem remote at the present time if there is a possibility of their future use. Further, we must be assured that the types of artillery we retain or develop are brought to the highest state of effectiveness of performance and reliability of operations under all possible conditions of warfare; and still further, that these types are capable of being produced, supplied, and maintained as required.

Artillery research and development is such a broad subject that only a few trends can be mentioned briefly. In guns we must attain more firepower, higher muzzle velocities, and greater striking effects. In contrast with earlier designs, wherein thick walls covered up many unknowns, we must investigate gun steels of higher physical properties, determine the mechanics of progressive stress damage, evaluate many similar physical and chemical phenomena, so that we can more scientifically select factors of safety to give desired performance with minimum weight and acceptable replacement factors. Further improvements are desired in the strictly mechanical features of guns: rifling, breech and firing mechanisms, chamber designs, obturation, facility of loading, and similar devices. In gun mounts and carriages, we should strive for greater mobility in all types of terrain, increased rates and greater flexibility of fire, and improved accuracy through simplicity and facility of operation. To achieve these ends, extensive research and development are necessary in the fields of metallurgy, flotation, suspensions, mechanical design, and power operation. In fire control, research and development must find means and methods of operating against the 1000-miles-per-hour target and the invisible target at any speeds. Recent scientific advances have created a field of fire control development practically without limitations.

To sum up, great progress has been made, and still much remains to be done. The principal problem confronting us is not what to do but how it shall be done. During the war period, we have made great strides, largely through the help of industry and scientific agencies converted to war work. The Ordnance Department has worked closely with these scientific agencies and with industry in research and development for the furtherance of our war effort. If we are to continue our weapon supremacy, this cooperation must continue with the time element as the only factor diminishing in importance. For future preparedness, the Ordnance Department needs scientific advice and industrial assistance. Wars are no longer strictly military affairs; they are national. We must be prepared in all fields of national endeavor.

From close contacts during the present war, the Ordnance Department has learned that scientists, industrialists, and labor are conscious of their responsibilities to prevent future wars, but that their principal concerns will be directed in other fields during peacetime. To maintain adequate preparedness, it is essential that sufficient funds be made available to continue research and development during years of peace with cooperation of both scientific and industrial agencies.

SMALL ARMS AND SMALL ARMS AMMUNITION RESEARCH AND DEVELOPMENT

By Colonel R. R. Studler
Chief, Small Arms Development Division

IT is a fact that there is not a single soldier in the Army who is unaffected by the work done by the Small Arms Development Division.

The Research and Development Service of the Ordnance Department, of which the Small Arms Development Division is a part, is responsible for

bringing into being those items of new or of improved Ordnance materiel required to insure that troops in combat shall be adequately armed. Superiority over enemy equipment is always an object.

Without going into great detail it would be difficult to describe all of the many responsibilities included under the title "Small Arms." Briefly, the Division is concerned with the research and development related to pistols, rifles, automatic and special weapons, and their ammunition up to and including caliber .60, as well as helmets and body armor.

The Division is organized along what might be termed commodity lines and is comprised of six branches. These are Administration, Armor, Rifle, Machine Gun, Ammunition, and Special Weapons branches, each concerned with the functions and types of arms its name indicates.

Actual Small Arms research and development work may be conducted by Government agencies, such as the Arsenals and Laboratories, or by contract with a commercial facility. In either case the work to be done is supervised and guided by the Small Arms Development Division of the Research and Development Service. In the case of small arms, Government activities are centered at the Springfield Armory, the Frankford Arsenal, and the Rock Island Arsenal. In each case where a commercial activity has been utilized for development work, an attempt has been made to select one where the work to be done shall be of a character similar to that with which the particular activity is normally familiar. It may be said that the Ordnance-Industry team has produced results which have had a far-reaching effect on Ordnance designs and gone far toward the successful conclusion of many development programs.

During times of peace there are opportunities for ideas to crystallize and time is not lacking for careful investigation of all the phases of a development problem which can be visualized. Notwithstanding the most careful study and the most complete cooperation in the final judgment of all concerned regarding the suitability of Ordnance equipment for combat use, it has been the experience through the years of this war that nothing is permanent. The North African Campaign was fought on terrain which is entirely different from that found in the Islands of the Pacific and the hedgerows of Normandy. These differences pose problems of tactical use of weapons which are again different from those resulting from the topography of the interior of Germany after the crossing of the Rhine. Under these circumstances demands for new developments have increased at a vastly accelerated rate. Use of standard weapons available has resulted in demands for changes, which in turn have required extensive development work that they might be put into effect. As a result of experience through the war, it is evident that the opinion held by some during our previous years that we had reached the peak of development and design was wrong to such an extent as would hardly have been believed possible. During the three years and more of war that have elapsed since the Japanese attack on Pearl Harbor there have been about 200 small arms items alone approved through the agency of the Ordnance Technical Committee for inclusion in the Supply Program.

Designs cannot be frozen at the beginning of a war, and it is a fact that changes are inevitable. It possibly would not have been necessary to do so much in such a short time had the attitude of the nation with respect to all things military not been such as to reduce appropriations not only for research and development but for production to below the minimum required to keep alive the art of Ordnance design and production.

It will be remembered that small arms in general are provided for equipment of the individual soldier. Most small arms have to be carried by manpower into battle. The constant trend of development has been toward lightening the load of the soldier so that his mobility and ability to undergo long periods of extreme exertion might not be reduced. Again it may not be generally known, but approximately 99 percent of the armament of airplanes for aerial combat is comprised of machine guns. There is a constant demand that machine guns for aircraft armament shall be light and at the same time more reliable in functioning. It will be seen that both in the air and on the ground, lightness is a desideratum which cannot be forgotten. In air to air fighting, in ground to air fighting and to a considerable extent in combat on the ground, high velocity for small arms projectiles is desired because of the reduction of the time of flight from gun to target which may result. A third trend of development has been increased fire power by increasing the cyclic rate which can be obtained for automatic weapons. The general trend of small arms development has been and will probably continue to be toward lightness, toward high velocity, and toward increased fire power. It must not be

FIG. 1. 50-caliber machine gun, Browning AN-M3, with solenoid for electric firing.

forgotten that the tradition of small arms in the United States is such that any individual must be assured that he can pick up any gun and find that it will function reliably.

To build reliability of functioning into weapons in which lightness is required, combined with the high powder pressures necessary for high velocities, poses a task which is most difficult. This task requires constant study by the designer, not only of interior ballistic problems, but of the kinematics of machines as well as the chemistry and metallurgy of the various items which go to make up the complete weapon.

It has been previously indicated that a considerable number of developments have been brought to completion during the war years and it may be of interest to describe a few of these.

One of the most important developments should be of particular interest to the physicists because it was not accomplished until laboratory methods of analysis were extensively applied.

The Caliber .50 Browning Aircraft Machine Gun, M2, was the standard in use by the Army Air Force at the beginning of the present war. It weighs 62 pounds and its rate of fire is 750 to 850 rounds per minute. While this gun is an outstanding weapon, and while indeed it has performed in an astonishingly good manner, parallel developments in aircraft tactics and other military equipment soon brought forth requirements for more fire power.

Initial attempts to increase the rate of fire consisted in applying well-known remedies and expedients, such as muzzle booster and the like. These readily produced the rate of fire desired, approximately 1,200 shots per minute, but unfortunately the guns were not satisfactory and failed to pass the tests because of an excessive number of malfunctions and breakages.

The next step, having been thus informed of weak places in the mechanism, was to maintain the high rate of fire and to strengthen the weak parts. This method, too, has its results. Such a course, however, often introduced new causes of trouble as fast as it eliminated others, and a third independent approach to solution of the problem was found necessary.

The new approach, and the one which eventually proved to be successful, was that which applied fundamental principles of mechanical analysis. A critical study was made of the gun mechanism; existing kinematic records were studied and points of sudden momentum and energy change were noted for further analysis. The rate of loading of the springs and their energy content when other parts of the gun were in violent motion were determined. Trunnion reaction data were checked against time-displacement data, and discrepancies and agreements were investigated.

When the facts concerning the functioning of the gun had been thus organized, certain obvious weaknesses of the mechanism and energy-robbing points were discovered. The gun designers were instructed to concentrate their attention upon these trouble-making points, and the experimental guns produced in accordance with their designs showed immediate promise. A kinematic check of these models to determine where practice disagreed with theory revealed a few errors in the original deductions. When these were rectified, the final gun performed in a very satisfactory manner and was soon adopted as the new Caliber .50 Aircraft Machine Gun, M3 (Fig. 1).

In any automatic weapon, transformation from the semi-automatic or self-loading type to the full automatic type can theoretically as a rule be readily accomplished. In practice, there are times, however, when such an alteration involves a very material change in the gun. Demands from combat areas for increased fire power resulted in the initiation of a project to alter the Caliber .30, M1 Carbine, a semi-automatic weapon, to deliver selective semi-automatic or full automatic fire. This project was initiated on May 24, 1944, and 21 days later a firing model was available for test. This was possible because the mechanism of the M1 Carbine was such that the change could be made without extensive alteration of the receiver and operating parts. The altered carbine contains seven new parts including springs and rivets, two new parts to replace old parts, and five standard parts slightly altered. The increase in weight resulting from the alteration was negligible, a matter of some two ounces. Insofar as the exterior appearance of the carbine is concerned, the only evidence of the change is the selector which is required in order that the gun may be made to fire either full or semi-automatic at the

will of the person using it. The M2 Carbine (Fig. 2) was made standard in September, 1944, or approximately four months after the project was started, and many thousands are now in use.

The physicist of today has reached out for new regions to explore so that he is a far cry from the position of even 20 years ago. Advances in the knowledge of physics have furnished the small arms ammunition designer with a key to many problems. But there are still many remaining to be solved. For example, the mechanism of propellent powder ignition is not definitely established. The law of gas friction in gun barrels under conditions of turbulence, high velocity, and temperature has not been determined. Even the pressure time curve, measured by means of the piezo gauge, does not truly represent pressure phenomena along the barrel at any given instant.

However, it will be remembered that a gun is a heat engine designed to transform the heat of burning powder into mechanical energy; therefore, the basic principles of thermodynamics may be applied to the solution of the problems involved in computation of interior ballistic data. Progress has been such that it is entirely possible to predict fundamental design characteristics required to produce a specified ballistic performance.

Practically every modern military small arms weapon is either automatic or self-loading, in which the principles of machine design are involved. Notwithstanding the possibility of application of kinematic analysis to the design of machine gun mechanisms, relatively little along this line has been accomplished, except as described in the development of the caliber .50 machine gun. It is a fact that the machine gun designers, of whom there are only a few, are usually content to apply the results of experience, without investigation of the fundamental problems involved.

The value of careful study and analysis of the functioning of the various parts of machine gun mechanisms is well evidenced by the results of some recent work in connection with the development of preformed wire stranded springs.

In any automatic weapon, we have a two-phase repetitive cycle in which the second phase is accomplished by utilization of energy stored in a spring. In the first phase, this energy is derived from either the movement of a piston through the agency of the powder gas or from recoil, depending on whether the gun is gas or recoil operated.

FIG. 2. 30-caliber carbine with 30-round magazine for automatic fire.

The proper functioning of the operating spring is essential in any machine gun mechanism. It is a matter of common knowledge that, as a result of vibration, a surge or wave motion may be produced in the coils of a spring, resulting in much higher stresses than those predicted by conventional methods of calculation.

In machine gun springs which are relatively long in respect to their diameter, time is required for motion originating at one end to reach the other end; and after the end has been reached, the disturbance is reflected toward the moving end of the spring, and so on. The nature of the wave motion thus induced in the intermediate coils of the spring is influenced by the relationship between the velocity of propagation and the velocity of displacement. In such machine gun drive springs, the resulting motion produces higher stresses in the end coils than in those more centrally located. The maximum stresses and the stress range are both very much greater than would be anticipated. In the machine gun this condition is aggravated because the rate of oscillation in the applied stress cycle approaches the natural frequency of the spring rather than the lower order of the cyclic rate of fire of the gun.

It has been found that because of increased damping resulting from friction between the coils in a spring made from preformed wire strands, this type of spring will operate in a stress cycle of about 50 percent of the range of that for the equivalent round wire spring, when subjected to vibration as in a machine gun mechanism.

Preformed stranded wire springs used in machine guns have shown useful life materially in excess of that obtained with the conventional single wire, and are presently being extensively used. Thus, by application of sound principles of analysis a notable advance in machine gun design has been accomplished.

Any mechanical design involves compromise. This is true whether the mechanism is a machine gun, an automobile engine, or any one of many other types which may be envisioned. The principal required performance characteristic takes priority over other considerations in the

design of weapons; for example, if the highest velocity is required, provision must be made for the maximum strength of the gun barrel and for the maximum size of powder container. Weight and other characteristics must be secondary. On the other hand, where velocity considerations do not require that maximum performance within a given caliber shall be obtained, the normal procedure is to seek minimum weight. This is particularly true in automatic weapons used by the air forces and by the ground troops; perhaps more so when the weapon is required primarily for use on the ground than in the air.

In general, it may be said that the four primary requisites in small arms: namely, reliability, minimum weight consistent with performance, reasonable ballistic performance, and firepower will continue to govern designs until something entirely new in the line of weapons is produced.

ROCKETS AND MISSILES

By Colonel G. W. Trichel
Chief, Rocket Development Division

THE Rocket Development Division of the Research and Development Service is charged with the development of rockets and other jet-propelled ordnance and their components and accessories. Prior to its organization in September, 1943, a considerable number of rocket projects were in progress under the supervision of various agencies. Hence, the formation of this Division did not initiate rocket development but merely brought together in one place the control of all rocket projects. The Division is organized into five Branches: Planning and Reports, Components Development, Weapons Project, Guided Missiles, and Engineering.

The Planning and Reports Branch is responsible for the coordination of projects within the Division. It controls the assignment of nomenclature to development items and controls priorities assigned to projects within the Division. It also recommends priorities to be assigned to rocket projects at Ordnance establishments. Test programs and directives for the test of items at the Ordnance Research and Development Center, Aberdeen Proving Ground, and by the Service Boards originate in this Branch. The Planning and Reports Branch is responsible for the maintenance of development records, progress reports, and the follow-up of critical projects. Ordnance Technical Committee action concerning rocket projects is instituted by this Branch. As a part of its liaison function, it receives, evaluates, and distributes technical reports. The tremendous volume of technical reports on our own and enemy rocket projects makes this function a rather important one of those allocated to the Branch. In this connection it renders an important service by briefing reports of other agencies, United States and foreign, in a short index published weekly. The Branch also maintains a cross-index of rocket literature for the benefit of the Division.

The Components Development Branch is charged with the institution and supervision of the necessary fundamental research to provide suitable components required to make up satisfactory rocket weapons. It organizes and directs propellent research, including new composition and grain design; supervises the procurement of experimental powder from Ordnance sources, and arranges for priorities between these sample orders. The Fuze Section engages in the development and testing of new types of rocket fuzes and attempts to provide fuzes to meet any special needs of various rocket weapon projects. Studies of the interior ballistics of rockets are also supervised by this Branch.

The Weapons Project Branch is devoted to the direction of projects for the development of complete weapons to meet military characteristics which have been prepared by the using arms. Each officer and engineer supervises a number of projects for the development of generally similar rocket weapons. The Branch has sections devoted specifically to the development of rockets, launchers, and special devices. The project officers look to the Components Development Branch for the necessary elements which can be combined into a complete weapon to meet a military requirement. In consultation with the Industrial Service Division concerned, they select a suitable facility and arrange for development contracts to be placed by the Ordnance Districts. The project officers keep in close touch with the developments throughout the design and manufacture of models for test. Ordinarily, they witness tests of their devices at the proving ground and service boards. Usually, the same officer has control over a project from the initiation of development until it is completed by rejection or standardization.

The Engineering Branch provides engineering service to the Weapons Project and Components

Development Branches. It assists in the preparation of lay-out drawings and design studies as required. The Engineering Branch also prepares the initial drawings for transmittal to the Industrial Service when manufacture of an item is decided upon. Drafts of specifications are submitted on complete rocket items for consideration by the Industrial Service Division concerned. The Engineering Branch performs an important function in the transition of an item from the experimental to preliminary manufacturing stage. This Branch maintains close liaison with the production engineering staffs of the Industrial Service and, by its advice to the operating branches of the Rocket Development Division, helps to maintain standard design which will be consistent with the manufacturing facilities available. It attempts to avoid the submission of designs with difficult or unsuitable tolerances or other unreasonable requirements which might make rocket manufacture in quantity difficult or impossible. By studying the difficulties being encountered in current manufacture, it is in a position to advise project officers and engineers of weaknesses to be avoided in future developments.

The design of modern military rockets began in the United States about five years ago. Since that time it can reasonably be said that there has been tremendous improvement in rocket weapons produced. Some of these, such as the shoulder-fired bazooka (see Fig. 1) and the aircraft-launched rockets (see Fig. 2), may almost be said to have shortened the course of the War. The bazooka has provided the infantry soldier with a weapon which he is confident can defeat at short range the most powerful armored vehicle. In the air results have been equally far-reaching. Airborne rockets provided a powerful weapon for the attack of German submarines by aircraft. In the later phases of the war in Europe, airborne rockets, in effect, provided flying artillery for the attack of objectives requiring larger projectiles than those afforded by standard automatic weapon equipment. On the enemies' side it can safely be said that rockets fired from aircraft stopped the daylight bombing of Germany without fighter escort.

These accomplishments were not readily brought about. From the beginning the design of rockets presented many fundamentally new research problems which had to be solved before satisfactory weapons could be produced. Most rockets use double-base, smokeless powders of various compositions as a propellant. However, the conditions of burning in a rocket are very different from those occurring in guns and at first little was known of the fundamental nature of the burning of smokeless powder in open chambers. Burning rates for rockets were not generally very different from those encountered in cannon. In the case of larger rockets greater web thicknesses were required than could be made by normal solvent powder processes. In order to achieve satisfactory results, it was necessary to develop new compositions of propellants and new and radical methods of manufacture. Prior to the beginning of the rocket program, nitrocellulose powders had never been manufactured in this country by dry extrusion. At present many million pounds per month of thick web, dry extruded, double base powders are being made. The development of such propellants and the difficulties attendant upon manufacture appeared almost insurmountable only three years ago.

FIG. 1. Rocket launched by bazooka.

Little or no information existed on the ballistics of unrotated, fin stabilized projectiles employed in high-angle, low velocity, mortar fire. In order to develop rockets, it was necessary to devise measuring apparatus suitable for the recording of data and to evaluate and develop from these data a system of ballistics for this class of projectiles. Even with those rocket projectiles stabilized by rotation, many new factors were introduced due to the long burning time and attendant acceleration in flight.

In general, temperature problems are greatly accentuated in the ballistic behavior of rockets. For instance, a change in burning time produces little change in final velocity, but it does produce a change in the length of the propulsion phase

FIG. 2. P-47 pursuit plane mounting launcher tubes for 4.5" rocket.

and consequent change in the effective elevation.

Completely new fuzes were generally required for rocket projectiles. Because of the low acceleration great difficulty has been prevalent in providing fuzes which will function properly under all firing conditions and still have satisfactory safety factors.

The storage and handling of rockets present problems which are peculiarly different from those of standard ammunition. For instance, in case of fire, complete rockets, being self-propelled missiles, may be launched into the air and create a serious hazard over a greater distance than would be caused by the explosive of the individual round in place. Thus, disassembly of the round to avoid such a hazard creates a major problem for the using arm, which must carry outfield assembly before the rockets can be used.

A satisfactory solution has been found to some, but by no means all, problems of rocket development. A fruitful field for research and development still remains to be investigated.

In the development of rockets, it was necessary to overcome many difficulties beyond the fundamental problems of rockets themselves. For instance, in most cases a development agency has the benefit of the advice and experience of the user in determining the characteristics which a weapon should meet. In the beginning the rocket development agencies had no such source of information available. The using arms could not describe the kind of a rocket wanted because there was no previous experience on which to base a requirement. Many decisions had to be made as to the operational possibilities of rockets which could have been certainly answered only by actual use. Decision as to calibers, ranges, and launching equipment all presented this same problem. Many details of the best organization and tactics for the employment of rocket weapons still remain to be worked out. In spite of these difficulties there have been produced suitable shoulder fired, anti-tank rocket weapons, and a medium caliber rocket adapted to the attack of area targets and capable of greater rates of fire than can ordinarily be achieved by organizational artillery. As has been previously mentioned, airborne rockets have been provided which have successfully attacked surface vessels, submarines, armored vehicles, anti-aircraft emplacements, and other land installations. The use of rocket barrages to cover amphibious landings has become almost axiomatic.

In carrying out this development program, the Ordnance Department has made use of several different types of agencies. These include Ordnance establishments, National Defense Research Committee projects, and contracts with private industry. Most of the early development work in the rocket field was done by Ordnance and NDRC groups working cooperatively in this field. Later, a rocket division was set up as part of the Ordnance Research and Development Center, Aberdeen Proving Ground, Maryland, and this group have made valuable contributions to the Army rocket developments. Since manufacture of rockets has familiarized a number of private companies with rockets, certain development contracts have been placed with these companies. As mentioned before, the early work was done in close collaboration with NDRC. The various NDRC development agencies still remain the most important single source of rocket developments. The Ordnance Department maintains liaison groups with Section H and Section L of Division 3, NDRC. The Ordnance Department also participates in the development and testing carried out by the Army Air Forces and their rocket test station. Research and Development Service maintains a suboffice at this station to participate in tests and developments carried out by Army Air Forces.

The developments which have been standardized to date have by no means exhausted the possibilities of further rocket developments. On the contrary, there is an ever-increasing trend towards greater use of rockets and jet-propelled devices both as principal weapons and as accessories in warfare. The Rocket Development Division expects to provide and maintain facilities to meet these needs as they arise.

TANK AND AUTOMOTIVE DEVELOPMENT

By Colonel Joseph M. Colby
Chief, Engineering-Manufacturing Division, Office Chief of Ordnance-Detroit

THE early phases of this war demonstrated the great military advantages of substituting horsepower for manpower, so that fewer men can have greater firepower, more mobility, and armor protection. Assuming leadership and trained manpower to be equivalent, the only advantages which one army has over the other is in its equipment. Hence, it is essential that Ordnance not only keep abreast of foreign developments, but be far in advance of them.

The Chief of Ordnance, Lieutenant General Levin H. Campbell, Jr., in the early stages of this war when there was great pressure to stop development and to freeze design for the duration to facilitate production, insisted that development continue at an accelerated rate. It is interesting to examine our production schedules and to note that all track-laying combat vehicles now being produced have been developed in the past two and one-half years. The huge requirement for new mechanized equipment of many types made it necessary to bring military engineering out of the secret rooms of the War Department and to decentralize it to the many engineering organizations of Industry.

General Campbell reorganized the Office, Chief of Ordnance, creating at that time the Research and Development Service, which he placed under the leadership of Major General G. M. Barnes.

During August, 1942, those divisions of the Office, Chief of Ordnance which dealt principally with tank-automotive equipment were moved to Detroit to form a tank-automotive product center in the heart of the automotive area. The Office, Chief of Ordnance-Detroit, is now commanded by Brigadier General Walter P. Boatwright.

The pattern of dealing with industrial groups has already been established by the Ordnance District system. This widespread decentralized organization informs the Development Divisions of the Ordnance Department of available engineering capacity to do needed work. They negotiate the necessary contracts, handle all legal and fiscal matters, facilitate procurement of supplies, and inspect and accept the product for the government. The engineering supervisory responsibility remains with the Development Divisions.

All the engineering work could have been centralized in a governmental engineering center, which would have had supervisory advantages, but the system selected is sound because it leaves the engineering groups near their experimental facilities. It also retains and fortifies the engineering groups of our industrial firms, permitting them to enter the post-war era with balanced organizations.

Our military problem was unfamiliar to many people in industry and to many new officers and Ordnance engineers. While cost is important, reliability is paramount. The production advantages of using standard commercial components had to yield to new designs giving greater consideration to functional concept, ruggedness, dust-proofing, water-proofing, corrosion-proofing, minimum bulk, and minimum weight.

The time element attained new importance. Some developments became obsolete before they were completed. A new mechanism has its greatest pay-off only if it reaches the battlefield in quantity before the enemy has time to develop a countermeasure. The Ordnance-Industry team developed mechanized equipment which has dominated all the Allied battlefronts of this war. This teamwork is one of the finest expressions of the working of an intelligent democracy.

The field of wheel transportation is largely an adaptation of standard commercial vehicles, or vehicles which have been designed in accordance with commercial procedure. Hence, in this field, the change of engineering thought is not as radical as it is in that of combat vehicle design.

The greatly expanded truck program, the news stories and pictures of the Red Ball Highway from Cherbourg to the front, and the shortage of tires, are all indications of the tremendous importance of wheel transportation to the mobility of armies. Destruction of railroads by bombing and enemy demolition demands that they be supplemented by wheel motor transportation. Further, motor transportation has permitted armies to move in areas where railroads were not available. Consequently, development stress is now being placed on large capacity, all wheel drive, high ground clearance, flotation-tire, wheeled transport vehicles.

In the field of tactical or battlefield transportation, the round wheels have given way largely to tracks. "When in doubt use tracks" is now a popular adage. There is a border line field, however, where the potentiality of the wheel has not been fully exploited. This field is being in-

FIG. 1. Light tank, M24.

vestigated now. Tracks should never be used where wheels will do the job.

We entered this war with the light tank, M3, and the medium tank, M3. In May, 1941, the design of the medium tank, M4, was settled and the detailing sufficiently complete to begin the construction of pilot models. These were all good tanks. Mr. Churchill stated before parliament that, "The General Grant (medium tank, M3) stopped Rommel at El Alamein; the General Sherman (medium tank, M4) defeated him." However, there were those who realized that the Germans would not rest content with outmoded equipment. To meet this threat of new, more powerful German materiel, the Ordnance Department continued intensive development on tanks and other tracklaying vehicles.

To make a thing bigger does not necessarily mean that it is better. The aim of development is "to achieve more with less." The basic theme of tank design is the combination of maximum reliability, mobility, firepower, and armor protection with minimum vehicle weight.

The development of any machine centers basically on the development of its components. Hence, our development program has stressed the development of components in order that military vehicles, for any purpose and of any size, can be constructed of thoroughly proved and tried elements. This enables us to turn out quickly a new vehicle with new tactical concept in the least time and with the best assurance that it will be mechanically reliable.

Components must function reliably as intended, be of minimum bulk, occupy the least possible space, and be of minimum weight. Lighter weight components will also enable more or larger guns, greater quantities of ammunition, and thicker armor to be carried.

For satisfactory performance a tank requires a powerful engine or large horsepower-to-weight ratio. The 76-mm gun motor carriage, M18, and the airborne tank, M22, because of their light armor basis, have been able to achieve this ideal. Size and bulk of large power-plant installations, with provision for suitable cooling and with an adequate power train, normally requires such bulk with resulting increase in weight as to make this high horsepower-to-weight ratio impractical for the heavier tanks. Developments are nearing completion now which will considerably aid this condition.

We would normally prefer air-cooled engines for tanks because less air is required for cooling and less difficulty is experienced when operating at the extremes of temperature. The radial air-cooled R975-C4, as installed with a torque converter type transmission in the 76-mm gun motor carriage, M18, is considered a nearly ideal installation. The Ford V-8 water-cooled tank engine has been very satisfactory because it met functioning, bulk, and weight requirements. The twin Cadillac engines, as used in the light tank series, have also given excellent performance. It is our desire to standardize on a series of engines with a standard cylinder, but it is doubtful if technological advancements, not only in reciprocating engines, but also in other fields, such as gas turbines, will ever allow us fully to reach this standardization ideal.

The effective utilization of power developed by an engine is determined largely by the mechanism transmitting this power to the ground. Our trend in transmissions is toward the infinitely variable type where full power of the engine is available at any speed of the vehicle, and where shifts by the driver are not required but are done automatically or by finger tip shift under full torque load. The elimination of the clutch and the substitution of the new types of transmissions have increased reliability, decreased maintenance, increased over-all performance, improved maneuverability, and decreased drivers' fatigue.

Our controlled differential type of steering, brought into tank design in 1932–1933, has been a simple solution to the steering problem and has resulted in very reliable performance. Industry is working on steering mechanisms which will include other important characteristics, such as finger-tip control and pivot turning, but these features will not be incorporated in design at the expense of reliability.

Because of the development of high power internal combustion, engines of lighter weight and reduced bulk, available horsepower is no

longer the limiting factor of mobility over battlefield terrain. Speed is limited by the suspension, which provides flexibility and shock-absorbing capacity between road, wheels, and hull.

The existing volute spring bogie suspension, as used on the light tanks, M3 and M5, and the medium tanks, M3 and M4, is simple and reliable but is subject to criticism from a functional viewpoint where speed is a basic consideration.

A torsion bar suspension for high speed vehicles designed in 1933 was not developed until the initial pressure of arming ourselves and our Allies was over. The 76-mm gun motor carriage, (T70), M18, with a top speed of 55 miles per hour, was the first production vehicle to be so equipped. The functional objectives were achieved in these initial designs, and this type suspension developed great popularity with all personnel familiar with it. The military importance of the torsion bar suspension derives from its superior shock absorbing capacity.

Tracks provide flotation for traversing soft terrain, bridging gaps, or negotiating obstacles. Grousers insure tractive effort. The track is the most abused part of the tank, can be a source of great power absorption, is subject to extensive wear, and as a result, is one of the most difficult problems in high speed track-laying development. Deep steel grousers are desired for operation in mud and clay, but they tear up roads and decrease tractive effort on surfaced highways. Rubber tracks are normally desired when long moves are contemplated over highways. The rubber joint, which was brought into our design in 1933, eliminates the objectionable pin wear, reduces friction losses, and cushions power train shocks.

Notable advances have been made in the development of electrical equipment. The adoption of the 24-volt electrical system, the requirement of suppressing electrical interference to radio operation, and the problem of protecting this equipment from dust, moisture, corrosion, and the effects of salt water were relatively new to the automotive field. Fuzes, switches, junction boxes, light bulbs, generators, coils, batteries, gauges, instruments, and a host of other electrical equipment needed complete reworking.

Early problems relative to air cleaners were increase in air cleaner efficiency and in service life, development of air cleaners for high horsepower engines, a program of standardization leading to fewer types, and consideration of air cleaner installation. Particular attention was paid to ruggedness, freedom from leaks, and location of the air inlet at the point of least dust concentration. Through group action of air cleaner manufacturers and the War Engineering Board, a single air cleaner which meets military requirements is now used on all vehicles, exclusive of the jeep, up to and including 2½ ton trucks.

Rubber has been one of our most critical problems. Upon Army Ordnance, the largest user of rubber, fell the biggest conversion job. It was not a simple matter of straight production substitution of synthetic for natural material, but an intensive step-by-step program of development and test over a three-year period.

Ordnance worked out its rubber conversion problems through Rubber Industry Committees, Ordnance supplying the test facilities, while the Rubber Industry pooled its personnel, laboratory, and processing resources to speed production.

The only purpose of a tank chassis is to provide mobility to the gun and armor protection for the crew. Tank design begins with the gun. Here again, more power and performance are desired for less weight and bulk. This trend is shown by comparison between the 75-mm gun mount, now used on the light tank, M24, and the 75-mm gun

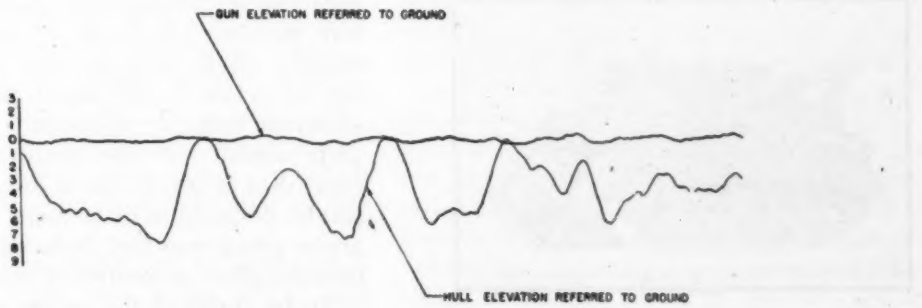

FIG. 2. Medium tank M4 traversing rough course at 15 m.p.h. with gyrostabilizer operating.

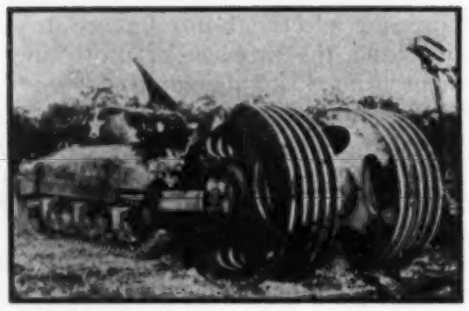

FIG. 3. Mine exploder.

mount on the medium tank, M4. Both guns fire the same round of ammunition with the same ballistics, yet the new gun is 45 percent lighter in weight, is $7\frac{3}{4}$ inches narrower, and is $4\frac{1}{2}$ inches less in height. It was this gun which made the light tank, M24 possible (see Fig. 1), giving it the firepower of the medium tank, M4.

We are the only nation which has the gyro-stabilizer for maintaining the tank gun on a line of sight, selected and varied at will by the gunner, when the vehicle is traveling cross-country. Its efficacy is demonstrated by Fig. 2, showing a plot, taken from photographic records, of the gun elevation referred to ground for various tank hull elevations referred to ground. This record was taken on a medium tank, M4, traveling 15 miles per hour across rough terrain.

Other fighting compartment problems include power control of the turret, gun elevating and traversing mechanisms, fire control equipment for indirect and direct fire, the shock mounting of all equipment, and stowage.

Since emphasis is placed on components their arrangement in a new vehicle has resulted in pilot models with a high degree of reliability, allowing early manufacture with minimum modifications. Thus our tanks combine greater fire power, more armor protection, and higher maneuverability with greater reliability than any other tanks of comparable weight.

FIG. 4. Tank recovery vehicle M32B1.

Development work does not stop with the completed truck, tractor, or combat vehicle. Unusual climatic conditions require desertization methods or winterization methods. Special conditions of operations make necessary the development of fording equipment or low ground pressure equipment. Special uses for bulldozers, mine exploders (see Fig. 3), and other equipment require special adaptation for specific functioning (see Fig. 4).

Finding ourselves suddenly at war, we had to yield on our requirements for standardization to allow use of existing facilities and to simplify procurement, training, supply and maintenance. The medium tanks, M4, M4A1, M4A2, M4A3, M4A4, looked a lot alike, but varied considerably

FIG. 5. Heavy tank M26, "General Pershing," which entered combat in March, 1945.

in the types of components used. The newly developed vehicles may not look alike, but all have a maximum number of interchangeable parts between them.

If we desire to give the large caliber gun maximum mobility, it should not be towed but mounted on a track-laying vehicle where adequate flotation is provided for maneuverability over soft terrain, where all its weight is used for tractive effort, and the time of going into and out of action is decreased. If the chassis has sufficient capacity to permit even a $\frac{1}{8}$" armor plate shield over the fighting compartment, a great deal of protection is provided. The vehicle can be designed so as to carry up to 12 inches of armor protection and probably more. This combination gives us protected mobile fire power.

To be ahead of the enemy on the battlefield, we must be one year ahead of him in production,

two years ahead of him in development, and three years ahead in thinking (see Fig. 5).

In this war the teamwork of Army Ordnance and Industry made available to the allied fighting forces the latest improved designs of mechanized equipment. Continuation of this partnership through the post-war period will enable our arms in the future to benefit from this association.

AIRCRAFT ARMAMENT

By Lt. Colonel George C. Gentry
Chief, Aircraft Armament Development Division

A COMPLETE history of the arming of aircraft would include three phases. The first would consider the installation in military aircraft of ground weapons; the second, the adaptation and modification of ground weapons for aircraft use; and the third would cover the development of specific weapons designed only for installation in aircraft and to meet the operational requirements of the Air Forces.

To supply our aircraft with adequate and efficient fire power is a task which presents tremendous research and development problems. It is impractical for many reasons to attempt to install in an airplane a weapon designed for the use of ground troops. Such weapons are too large, too heavy, and usually have a rate of fire much slower than that demanded by the conditions of modern aerial combat when an enemy plane may be "in the sights" for only a few seconds.

The Aircraft Armament Development Division of the Ordnance Department is directly responsible for the development of aircraft cannon of 20-mm and larger calibers, their related equipment and accessories, armor, flak curtains, airborne equipment, and assigned fire control instruments. The program for any one item would include the original conception and design, the building and testing of pilot models, the procurement of the materials and the industrial services necessary to carry the project through to standardization of the item, and its release for procurement. All engineering tests are supervised by representatives of the Division and close cooperation is maintained with those military, naval, and civil agencies which are interested in the development.

Paramount in all thought and in all design is that our forces must have arms which will establish and maintain supremacy over the enemy. Information leading to the development of weapons for future needs is obtained from the using services, from reports from Military Intelligence on enemy plans, and from the creative thought of the engineers and technicians of the division and of aerial tacticians. When a problem arises all the resources of the Ordnance Department are immediately applied to its solution.

Fig. 1. Partial right top view of 37-mm gun M10.

In 1935 the Chief of Ordnance and the Chief of the Air Forces agreed upon a program which still determines the working basis for the development of aircraft armament. Various caliber weapons were fired to determine their relative effects against aircraft structures. These tests determined the general military characteristics which a weapon must possess to merit its consideration as aircraft armament. The minimum muzzle velocity should be 2000 feet per second, the rate of fire should be as high as possible without affecting functioning, trunnion reactions of 4000 pounds were permissible, and the weight of any weapon should not exceed 2000 pounds.

A dual approach was made to the problem. A thorough study was made of all available weapons to determine their suitability as aircraft armament and, concurrently and with far more intensive study of details, the design and construction of entirely new weapons was undertaken. Those studies continue. Existing weapons are constantly being improved; newer, more powerful weapons are always on the drafting boards of the designers.

The 20-mm Hispano Suiza Birkigt, developed under French patents, was first tested by the Ordnance Department in March, 1938. The original weapon was quite heavy and the drum magazine accommodated only 60 rounds of ammunition. Ordnance research and development reduced the weight of the gun and replaced the awkward, heavy, drum magazine with a feed mechanism which permitted continued automatic fire from disintegrating link belts which carry hundreds of rounds of ammunition. Subsequent improvements have produced the current feed mechanism, lighter by seven pounds than the earlier model and with a 50 percent greater belt lifting capacity. Recently standardized, and cur-

FIG. 2. Nose section of a B-25 Mitchell bomber showing 75-mm cannon and the two 50-caliber machine guns located above.

rently being supplied to the Naval Air Forces, is the improved, shorter, 20-mm gun lighter by 20 percent than the original and with a rate of fire 125 percent as great.

The 37-mm aircraft cannon, next larger of the series, was designed and developed in this country (Fig. 1). Here, too, the Ordnance Department encountered the problem of magazine capacity insufficient for the requirements of aerial warfare. A disintegrating link belt feed was designed for this gun, its cyclic rate of fire was greatly increased, and its muzzle velocity stepped up to a point one-third greater than that of the original projectile.

The main objective of all artillerists, land, sea, or air, is to provide the greatest possible striking power at the right place and at the right time. This objective and the anticipation of future needs impelled the Ordnance Department to develop a 75-mm aircraft cannon.

Tests indicated that a 75-mm cannon was the smallest gun which would destroy an enemy aircraft with one shot (Fig. 2). For test purposes a 75-mm Model 1897 gun and recoil mechanism was installed in a B-18 Airplane which was modified to accommodate the weapon, the heaviest and largest caliber weapon which had yet been installed in any military aircraft. In flight tests the gun was fired at a towed target 3000 yards away and the results justified the faith of the Aircraft Armament Development Division that large caliber cannon could be mounted in aircraft.

In April, 1942, the Army Air Forces submitted the requirements for an airplane equipped with a major caliber cannon for the destruction of air and ground targets. A 75-mm gun was specifically designed for aircraft use and installed in an experimental plane. A novel feature of the modified weapon was a recoil-operated muzzle cover which closed the muzzle as soon as the projectile had passed from it. This prevented the gases of explosion being blown back into the gunner's compartment.

Later in the same year this gun was standardized and produced in quantity for installation in the B-25G series of medium bombers. The special aircraft mount which had been designed for the installation was standardized at the same time. Several Japanese destroyers and other craft have been sunk by this weapon.

A tremendous reduction in weight was necessary before a weapon as large as a 75-mm gun could be installed in an airplane. This reduction was obtained by designing a thin-walled, light weight, highly stressed gun tube and a concentric recoil mechanism of the hydro-spring type; and by mounting the piston of the recoil brake directly to the gun tube instead of to lugs machined on the breech ring. The latest model of this gun and mount weighs only 57 percent of the original 75-mm cannon designed for aircraft installation.

The need for protecting aircraft crews with armor plate was stimulated when automatic aircraft cannon were added to the machine guns which had been standard aircraft armament.

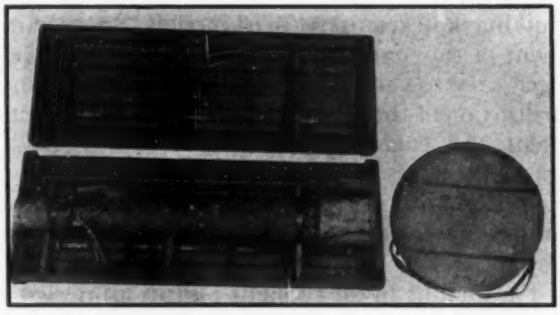

FIG. 3. Paracrate M5A2 with tube of 75-mm howitzer M8.

Military characteristics desired in armor plate are supplied to the Ordnance Department by the Army Air Forces. Tests are then made to determine the relative values of various materials and those most suitable are recommended to the Air Forces. In addition, tests are developed to control the uniformity of those materials in production.

The size and weight of much of the Ordnance materiel used by paratroops and airborne infantry prohibit the use of standard Air Force containers for the aerial delivery of the equipment. The demand for containers that could be dropped safely by parachute was met by the development of special containers known as paracrates. In these the particular item of equipment is held rigidly against movement by a series of felt-faced transoms. Containers built to carry equipment only, or equipment and ammunition, are called paracrates (Figs. 3 and 4); those which carry ammunition only are called parachests. A paracaisson is a parachest which carries among its contents a pair of wheels and a drawbar which permit its assembly into a cart after landing.

As an example of the development of this type of equipment, the 1440 pound 75-mm Pack Howitzer and its carriage are dropped in seven loads. Eighteen rounds of ammunition are dropped with the gun in one parachest and a paracaisson. Six of the nine loads are attached to the bomb racks of the airplane, three are carried in the plane and are thrown from the door.

The first paracrates for the 75-mm pack howitzer were of plywood. These were used in many airborne operations but continuing development has produced steel paracrates which are much more rugged than the plywood models. These may be shipped disassembled and occupy only about 40 percent of the space required by their wooden predecessors. Tests are being made of aluminum and magnesium alloy paracrates. Magnesium has a marked tendency to crack on impact but experimental aluminum containers compare favorably with the steel models and weigh about 45 percent less.

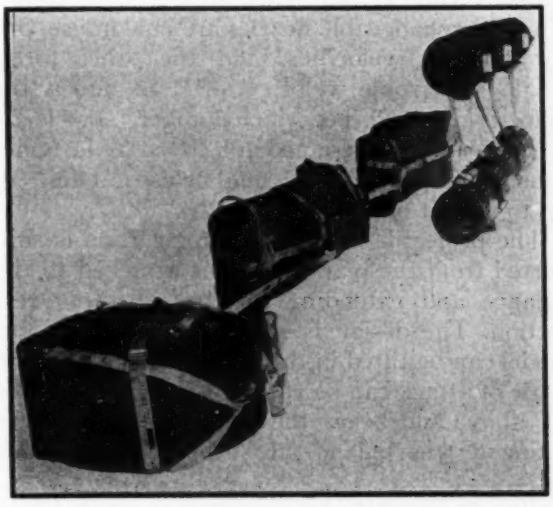

FIG. 4. Paracrates, showing control pattern harness M2.

In this field, the objectives to be attained are constantly reviewed and forecast in connection with new thoughts, new tactics and practices, new principles, materials, and techniques. As a result, the program of research and development is under constant revision to insure that when a new need arises it will be successfully met.

SOME RECENT ADVANCES IN BALLISTICS

BY THE STAFF OF THE BALLISTIC RESEARCH LABORATORY

Introduction

THE Ballistic Research Laboratory of the Ordnance Research and Development Center at Aberdeen Proving Ground, Maryland, an outgrowth of the Ballistic Section of the Proof Department of the first world war, was formally established in 1935. The directors of the Laboratory have been Colonel H. H. Zornig, 1935–1941 and Colonel L. E. Simon, 1941–. The Ordnance Research and Development Center is directed by Colonel G. G. Eddy and the Aberdeen Proving Ground is commanded by Major General Charles T. Harris, Jr.

Ballistics, the study of things hurled, thrown, or dropped, is conveniently divided into three parts: interior, which deals with the motion of the projectile and gases in the gun or of the gases of a rocket; exterior, which deals with the motion of the projectile or bomb in the air from the launching mechanism to the target; and terminal, which deals with the motion and the effect of the projectile or bomb, its fragments and its blast at or in the neighborhood of the target. The study of ballistics is the chief research aim of the Ballistic Research Laboratory, but from a practical point of view its other main function, that of preparing firing tables for army guns and bombing tables for all army bombs, is of great importance.

FIG. 1. The Ballistic Research Laboratory, Aberdeen Proving Ground.

During and shortly after the first World War, nearly the entire effort of the Ballistic Section was devoted to the preparation of firing, bombing, and exterior and interior ballistic tables. However, as time went on more and more experimental and theoretical research in ballistics was done. This gradually increasing tempo was greatly accelerated in 1940 when the Laboratory was fortunate to enlist the services of a considerable number of eminent scientists from the universities and other research institutions.

The staff of the Ballistic Research Laboratory is housed chiefly in two buildings, the main Ballistic Research Laboratory building (Fig. 1) and the Supersonic Wind Tunnels Laboratory. In addition, there are various smaller buildings, firing ranges, and a blast testing field.

In the following are given accounts of some of the recent work of the Laboratory. In these, the emphasis is placed on instrumentation to a somewhat unrepresentative extent because it is during this war that there have been developed specialized instruments for ballistic measurements without which important phases of ballistics could not be carried out. It seems also of more general interest than the actual experimental and theoretical work of the Laboratory.

1. The Supersonic Wind Tunnels

The recently constructed Supersonic Wind Tunnels meet an urgent need for rapid determinations of aerodynamic characteristics of projectiles. By suspending models on a delicate balance system in an air stream driven at various velocities, it is possible to measure the reactions quickly and accurately. This technique replaces to a considerable extent the slow and costly practice of manufacturing full-scale projectiles and testing them on the range. The technique is used for "trouble shooting" on projectiles in service, for checking or correcting new designs before production, and for assembling basic data for design in the future. Finally, it is hoped that the tunnels may be used more and more for the research work that will be required to develop the new field of supersonics for the advancement of science.

The Supersonic Wind Tunnels Laboratory is to be equipped with two closed circuit tunnels, powered by a single compressor plant. One tunnel, known as the Bomb Tunnel and destined primarily for the study of finned projectiles, was put in operation in December 1944. The second, or Ballistic Tunnel, is destined primarily for the study of spinning projectiles but operation awaits the completion of a flexible nozzle and balance system.

The power plant consists of five centrifugal compressor units operating in parallel or in series up to three stages of compression. A total of 13,000 h.p. is available. The air is filtered and dried, and a reserve supply, thus conditioned, is carried in a large storage sphere. These facilities permit the operation of the tunnels through a considerable range of pressures and densities, and, in particular, permit the control of Reynolds number and Mach number independently.

In the Bomb Tunnel, the air is driven through a *nozzle* to produce a homogeneous flow through a rectangular *test section*, 15 inches wide and 20 inches high, equipped with glass observation windows, 18 inches in diameter. Thereafter, the air passes through the diffuser, where the velocity is reduced (kinetic energy is transformed to pressure energy), and back to the compressors. Two interchangeable nozzles are now in use, one for subsonic velocities, and the other for a single supersonic velocity of 1.72 times the velocity of sound (i.e., Mach number,* $M=1.72$). A third nozzle, designed for $M=1.3$, is under construction, and others could be used, if desired, up to a limit of about $M=2.0$.

The projectile model undergoing tests is supported from the rear by a strut attached to the balance and extending forward into the test section. The design is such that the strut and model can be tilted in the vertical plane (i.e., the angle of attack can be varied) through a range of 10° above and below the horizontal. The forces acting on the balance are transmitted to dials

* $M=v/a$ where v=velocity with respect to air and a=velocity of sound in air.

which register drag, lift, and pitching moment directly in standard units.

Working conditions in the tunnel may be illustrated by the actual data for a typical run at $M=1.72$. The air in the supply section, leading directly into the nozzle, had a temperature of $+100°$F, a pressure of 30 lb. per square inch, and a density of 2.04 times normal atmospheric density. After passing through the nozzle into the test section, the temperature was $-108°$F, the pressure 5.9 lb. per square inch, and the density 0.64 times normal atmospheric density.

In addition to the measures of the reaction of the model to the airstream, the pattern of the airflow around the model may be recorded by means of an off-axis, two-mirror Schlieren system. A parallel beam of light, passing through the windows of the test section, is focused on a knife-edge, behind which a camera is located. With the knife-edge suitably adjusted, a sharply defined pattern of the airflow around the model may be observed on the viewing screen of the camera or recorded by photography.

A complete test of a model at a single Mach number includes dial readings at 1° intervals over the range of angle of attack from $+10°$ to $-10°$ and Schlieren photographs at 0°, 5°, and 10°. A test is made in about an hour and a half. For projectile models of normal length and a standard diameter of two inches, measures over the subsonic range of velocities appear to be reliable up to $M=0.85$, beyond which the wall effects become troublesome.

The tunnel was calibrated first by pressure surveys and then by the actual measurement of test bodies (spheres, cones, and wedges) whose aerodynamic characteristics were known. The results were in substantial agreement with those to be expected on the basis of theory or free-flight measures made on the spark photography firing range. Slight imperfections in the flow through the test section were found which, under certain conditions, might affect the measures by as much as three percent. The defects were due to irregularities in the nozzle and test section, and can be reduced or eliminated when the pressure of urgent work permits. Actual measures on a given model at a given tilt can be repeated under normal conditions to about one percent.

The Ballistic Tunnel, when completed, will handle models of any kind, spinning, finned, or winged, within the limitations of the test section. However, the provision for rapid spinning, at 20,000 to 40,000 r.p.m. and faster, emphasizes

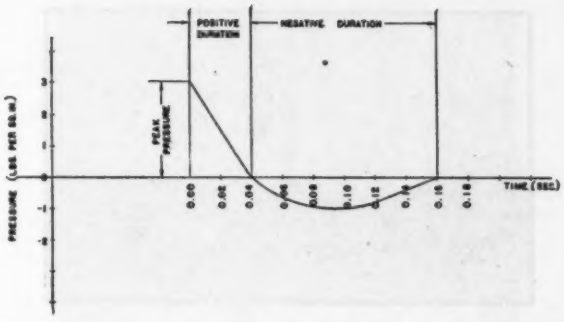

FIG. 2. Idealized pressure-time curve in the air blast wave from a 4000-lb. bomb at 300 feet from the bomb.

the immediate usefulness of the tunnel for the study of spin-stabilized projectiles. The tunnel is provided with a six-component balance and will operate up to Mach numbers greater than 4, with a $15''\times15''$ test section. The problems raised by the necessity for a different nozzle-shape for each supersonic velocity desired, is being solved by means of a flexible nozzle. The two vertical sides of the nozzle remain fixed while the top and bottom, which are thin plates of steel, are bent into the required shapes by means of a system of motor-driven jacks operating on cams. With this device it is expected that it will be possible to vary the velocities continuously with a minimum of time and effort.

2. The Measurement of the Blast from Bombs

The emphasis on aerial bombardment in the early stages of the war against Germany created a demand for objective and accurate measurements of blast which could serve as an index of performance of bombs, not only as a guide in the development of better explosives, but also as a test of our loading and detonating techniques. There was also need for quantitative comparisons of our bombs with specimens recovered or captured from the Germans so that full use could be made of studies of the damage inflicted on English cities in predicting the best sizes of bombs and the extent of bombing operations necessary to reduce enemy installations.

When a bomb is detonated, much of the resulting damage is caused by the changes in pressure occurring in the blast wave which propagates out from the center of the explosion with a velocity somewhat in excess of that of a sound wave. An isolated object exposed to the blast first experiences a sudden rise in pressure as indicated by the curve in Fig. 2, the amount depending upon the distance and size of the

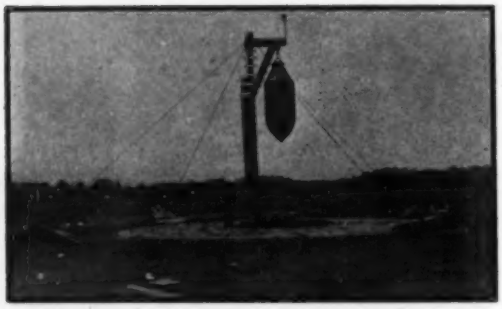

FIG. 3. A large bomb ready for detonation in blast pressure tests at the Aberdeen Proving Ground.

bomb. After a time, designated in the figure as the positive duration, which also depends upon the size and distance of the bomb, the pressure has returned to normal but it continues to fall to a value less than that of the normal atmosphere before normal conditions are again restored. The pressures experienced by a large object like a building are strongly conditioned by reflections. However, an index of those factors depending upon the bomb itself can be obtained from measurements made with a fast-acting pressure gauge mounted in a streamlined baffle which permits the air in the blast wave to flow past the gauge undisturbed. One such index is the peak value of the pressure which occurs at the instant of impact of the wave. Theory predicts and experience has shown that this quantity is a measure of the probability of damage to objects which break in a time short compared with the positive duration. The more important index of probability of damage to resilient objects, including most types of buildings, is the area under the pressure-time curve during the positive-duration phase, a quantity which is called the *positive impulse* and measures the momentum which would be imparted to unit area of a structure by this portion of the blast wave.

In the tests conducted at Aberdeen Proving Ground the bombs are hung several feet above the ground, as shown in Fig. 3, and several gauges are stationed a few feet above the ground at various distances from the bomb. The most direct and a very commonly used method of measuring the blast involves making photographic records of the pressure-time curves by means of cathode-ray oscillographs connected through suitable amplifiers to the gauges. The area under the curve on this record is determined graphically and reduced to absolute units by a static calibration of the system. A practical pressure gauge for this type of operation has been developed at the Ballistic Research Laboratory with considerable help from scientists working under the NDRC and from British scientific organizations working on this problem. This gauge consists of a stack of thin plates cut from piezoelectrically sensitive crystals and cemented together with silver foils between the layers to transport the electrical charge to the recording system. The assembly is potted in pitch in a heavy metal cup which serves to anchor the cable and to protect the crystal elements against light fragments. Such gauges respond faithfully to the high frequency components of the blast wave and indicate the sharp front of the blast wave shown in Fig. 2. At the same time the electrical resistance is high so that there is no appreciable leakage of charge while the blast pressure persists. The gauge is linear in its response and is easily calibrated in a pressure tank against an ordinary manometer. The signal strength is well above the level of microphonic effects generated in the connecting cable, and the gauge, though sensitive to thermal effects, is well insulated against changes in temperature such as might occur by absorption of radiation from the bomb or from the adiabatic compression of the air in the blast wave. With a readily obtainable sensitivity of one hundred microcoulombs per pound per square inch and a capacity in the connecting cable of .02 microfarads a pressure of one pound per square inch gives a signal of 5 millivolts. The recording system includes a stable direct-coupled amplifier of special design having an input resistance of 500 megohms and an over-all linear gain adjustable to values as high as 100,000. The output of the amplifier controls the deflection of the beam of a 3-inch cathode-ray tube, and a panel of eight cathode-ray screens are photographed by a single continuous-strip 35-mm camera with film speeds up to 1 cm per millisecond. Two complete recording units of this type, totaling sixteen channels, are shown in Fig. 4 as they are mounted in a special air-conditioned trailer. During the tests this trailer is housed in a fragment-proof concrete shelter 1000 ft. from the position of the bomb.

Another type of gauge in current use consists of a small pressure-sensitive condenser connected as the frequency-controlling element of a one-megacycle oscillator. The oscillator unit is contained in a thick-walled steel vessel from which

the gauge protrudes and its output frequency is transmitted over a field telephone line to the shelter where it beats with the signal from a constant-frequency local oscillator. The beat-frequency, which ranges from one to ten kilocycles in proportion to the pressure, is used to flash a small *neon lamp*, and the flashes are recorded on moving film as a series of dots. It is easily seen, from the fact that the dot frequency varies linearly with the pressure, that the positive impulse of the blast wave is proportional to the excess of the number of dots occurring on the film during the positive pressure phase over the number during an equal time interval before the incidence of the blast wave.

While the best measurements of positive impulse are obtained by the techniques described above, the highest accuracy in determination of peak pressure is obtained by a third technique, in which the velocity of the shock wave is measured and the peak pressure is calculated from the theoretically established Rankine-Hugoniot equation:

$$p/p_0=[2\gamma/(\gamma+1)](v^2/c^2-1),$$

where p is the peak pressure, p_0 is atmospheric pressure, γ is the ratio of the specific heats, and v and c are the velocities of the blast wave and of sound respectively. In applying this method to the measurement of blast pressures the two velocities are determined within a few seconds of one another by recording the times of arrival of the blast wave and of a sound wave generated by a small charge at two pressure-sensitive gauges separated by an accurately measured distance. The accuracy in the measurement of the velocities is about 0.1 percent, and the corresponding peak pressure has an accuracy of 1 percent. This method has the advantage that the pressures are measured without in any way disturbing the blast wave, so that questions of reflections and aerodynamic forces are completely avoided. It has been determined that values obtained in this way are more accurate than those resulting from usual methods of direct measurement because with the latter method scatter about the mean point would be about twice as great and actual systematic errors caused by inaccurate calibration may be as high as 10 percent.

3. The Ballistic Cameras

The Ordnance Department not only procures bombs for the Army Air Forces, but it also has the responsibility of supplying the ballistic data

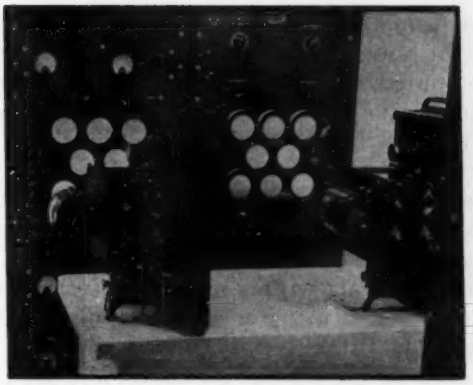

FIG. 4. Cathode-ray screens and recording cameras in the Ordnance Department's 16-channel oscillograph used in static detonation tests at the Aberdeen Proving Ground. In operation, a bright spot of light formed by an electron beam on each screen traces the changes in pressure accompanying the blast wave.

which determine where a bomb should be released so that it will find its target. This information is supplied to the bombardier in the form of a bombing table, which gives the trail* and a quantity representing the time of flight of the bomb, for various speeds and heights-above-target of the airplane. If the drag of the atmosphere were negligible, the bombing tables could of course be constructed by computation alone, but the forces of air resistance are important in their magnitude and can be evaluated only by experimental tests. These tests constitute what is known as range bombing and include for each type the dropping of a series of bombs from various altitudes together with measurements of time of flight, the velocity and height above target at release, and the range. From these data the effects of air resistance can be determined, and the complete bombing table can then be computed. To measure the time of flight, both time of release and time of impact are recorded. The range is determined from measurements of the coordinates of the airplane at the time of release and of the point of impact. However, the range depends strongly on the velocity of the airplane and its height-above-target at release. While position of release need be measured with only the accuracy consistent with the expected dispersion of the bombs on their target, the requirements are more stringent as regards

* If an airplane continued on the same heading after dropping a bomb, the point vertically below the airplane would fall a certain distance ahead of the impact of the bomb. The ratio of this distance to the altitude at release is the trail.

the determinations of the positions of the airplane in flight prior to release, from which the velocity is computed, since any error in the measurement of the horizontal velocity appears multiplied by the time of flight as an error in the range. For example, to obtain the required accuracy of measurement of velocity when the time of flight is about fifty seconds, it is necessary to determine the successive positions of the airplane at one-second intervals within an error of one-fiftieth the expected dispersion of the bombs on their target. The allowable error is but a very few feet even at the highest altitudes, and this part of the measurement requires a higher accuracy than that of the best available theodolites.

This problem has been solved at the Ballistic Research Laboratory by a photographic technique similar to that used by astronomers in measuring the positions of the stars. The airplane carries a bright lamp in its belly which flashes at regular and accurately-known time intervals, and as it makes its bombing run in the range bombing tests, two cameras stationed at either end of a long base line, with lenses pointed vertically upwards, record the succession of flashes as rows of regularly-spaced dots on their respective photographic plates. Careful measurements of the positions of corresponding dots on each plate determine the instantaneous directions of the airplane as viewed from each of the two camera stations, and the intersections of the two directions fix the absolute positions of the airplane in space.

As an example of a practical arrangement, the Ordnance Department ballistic range at Muroc, California, has two cameras of 12″ focal length at either end of an 8000-foot base line. The positions of the images of the lamp on the plates relative to a pair of fiducial marks can be measured with an accuracy of one sixty-thousandth of the focal length, and the fiducial marks are related to absolute spatial coordinates by photographs of the stars made at night with the cameras in the same positions. To assure that the positions of the cameras are the same during the range bombing tests and while calibration photographs are being made, an accurate bubble level is placed on the camera base in two mutually perpendicular positions to check its vertical adjustment, and any rotation about the vertical is detected by a telescope rigidly attached to the body of the camera and focused on a distant marker.

A difficult problem in making measurements by this method is the elimination of excessive skylight from the cameras when making a series of exposures on the same plate during the usual daylight operation. With lens apertures sufficiently great to register images of the airplane lamp at the usual altitudes of the bombing runs, it is necessary to limit the total exposure of the plate to skylight to about four one-hundredths of a second, and since as many as twenty exposures at intervals of one second are often desirable in order to bracket the release point, each exposure cannot exceed one five-hundredth of a second. This rather exacting requirement, together with the necessity of synchronization between the exposures of the two cameras and the flashing of the light in the airplane, is accomplished by a system of double disk shutters on the two cameras and a radio synchronizing signal which flashes the lamp in the airplane and, simultaneously, an auxiliary stroboscopic lamp at each camera position which enables the operator to examine his shutter and determine that it is actually open at the right instant. Once the shutters are in adjustment, they continue to open simultaneously since they are both driven by synchronous motors operating from synchronized a.c. power supplies. The frequency of the power supplies and the timing of the synchronizing radio signal are controlled by an accurate tuning fork.

The time of release is determined with respect to those at which the position photographs are taken by means of a recorded radio signal sent from the airplane at the instant the bomb shackle opens, and the time of impact is obtained on the same chronograph record by means of seismographs which are sensitive to the earth shock resulting from the impact.

The combined instrumentation is the product of the joint efforts of astronomers, physicists, and radio engineers, and from its use a new and higher degree of accuracy is being realized in the production of bombing tables.

4. The Ignition of Smokeless Powder

Smokeless powder consists of nitrocellulose to which have been added and suitably admixed several other ingredients, namely: a plasticizer to confer mechanical toughness; a stabilizer to prevent chemical degeneration; and possibly other materials with special functions as required. The resulting tough plastic is then formed into grains which, when touched with a match, burn vigorously, emitting hot gases from each unit

area of ignited surface at a rate which is approximately proportional to the ambient pressure.

By making use of these general principles (or refinements of them), it is possible so to adjust the total weight of powder, and the size and geometrical form of the grains, that a charge is produced suitable for a particular weapon, e.g., a gun. These parameters must be so adjusted that the projectile attains the desired muzzle velocity, and that the pressure never exceeds a limit accepted as a safe maximum for the gun. The state of the art is now such that these requirements can be determined by a competent ordnance engineer.

It is observed all too frequently, however, that a charge evolved as outlined above is nevertheless not a satisfactory charge. The physical arrangement of the powder within the chamber, the amount and grade of black powder contained in the primer and whose function it is to ignite the smokeless powder, and the location of the primer with reference to smokeless powder are all seemingly less important factors. Nevertheless, their qualitative effect on the burning process may be profound.

Consider, for instance, a gun for which there has been established by trial a suitable combination of primer and powder charge. When such a gun is fired, the black powder ignites, enveloping the powder charge in an atmosphere of intensely hot gases charged with hot solid particles. After a small but measurable delay (of the order of some milliseconds) the powder ignites, and the pressure rises smoothly, accelerating the projectile down the bore of the gun and ejecting it from the muzzle with a velocity which can be measured. If now one fires such a gun repeatedly, changing nothing except the amount of black powder in the primer which is progressively diminished, and directs attention to the time interval between the primer flash and the beginning of powder burning, the smoothness of the pressure rise, and the muzzle velocity of the projectile, it is found that up to a certain point, diminution of the primer charge has little effect on the quantities noted above. With less than this critical minimum present, however, a remarkable change takes place. The delay between the primer flash and the inflammation of the smokeless powder lengthens enormously, becoming in extreme cases several seconds, the pressure rise becomes irregular, and the velocities become erratic.

What causes this remarkable series of changes, and in particular what is the reason for this abnormally long hang-fire? When ignition of the powder does finally take place after several seconds, the originally hot gases from the primer must be greatly cooled, and it is difficult to see why, if these gases cannot ignite the powder while they are hot, they succeed in doing so after they have cooled off.

The explanation of this long hang-fire is to be found in the details of the mechanism by which smokeless powder burns, particularly in some of the details whose significance has only recently been grasped. This mechanism is now presented briefly as it is at present understood.

A cross section of a burning powder grain, perpendicular to the burning surface, would reveal that although the grain is immersed in the intensely hot gaseous products of its own decomposition, the interior of the grain is still at practically its original temperature. As the surface of the grain is approached from the interior the temperature rises, slowly at first, then more and more rapidly until at the surface a temperature is reached which, while still far below the temperature of the surrounding gases, is still high enough so that the material of the powder grain can no longer exist as a solid, but is decomposed into simpler gaseous compounds. This of course defines the solid-gas interface. An essential fact to keep in mind is that the region within which the temperature of the solid is changing appreciably is a very thin surface layer. The heat required for the maintenance of this hot surface layer and for its continual conversion into gaseous decomposition products has been assumed to come from the further reaction of these gases; and the higher the ambient pressure, the closer to the surface they generate their ultimate high temperature, the greater the heat transfer back to the surface. This is the means whereby the rate of burning depends on the pressure.

More recently, careful experimentation has shown that this picture has to be modified in the following way. It has been shown that the solid propellant is not merely so much inert material to be heated to decomposition by heat flowing into the surface from the surrounding hot gases, but that heat is also evolved within the solid by a preliminary reaction whose nature is not as yet fully understood. This much is known, however. The rate of evolution of heat is dependent on the temperature through a factor $e^{-E/RT}$, as in many chemical reactions, and for

this reason powder heated to a temperature at which the rate of heat evolution more than compensates for the loss of heat to the surroundings will progressively increase in temperature, eventually igniting.

This mechanism explains the long hang-fires previously described. If the amount of black powder in the primer is very small, then the surface layer of the smokeless powder is not only not heated to ignition during the primer flash, but is not even raised to a temperature at which heat is evolved more rapidly than it is lost to the interior of the grain. With somewhat more black powder in the primer, this latter limit is exceeded and the powder, although not ignited, is raised on the surface to a temperature such that its temperature is raised by self-heating, eventually to ignition. But during this period heat is also penetrating into the interior of the grain, and when ignition finally takes place the first layers to burn are hotter and for that reason burn more rapidly than the remainder, causing an initial abnormally rapid rate of pressure increase. The charge ignites, but its functioning is not altogether satisfactory because of this initial abnormally rapid pressure rise which can lead to erratic further rise in pressure. Finally, when the primer contains the optimum amount of black powder, the primer flash conveys to the smokeless powder enough heat to bring its surface to ignition quickly while the black powder is still burning. The use of black powder in excess of that required for rapid ignition does not influence further the burning of the smokeless powder, since the rapid exodus of gases from the surface of the latter after ignition provides effective insulation from the black powder gases. Thus it appears that there is an optimum ignition condition for each round which it is necessary at present experimentally to ascertain.

Conclusion

The foregoing discussion gives some examples of the variety of fields of research that are involved in the study of ballistics. In view of the fact that the prosecution of studies such as these provide the only certain means of ensuring that the fundamental data and theories needed for the continuing modernization of ordnance materiel are accumulated, that the military implications of future scientific advances are properly applied by the Ordnance Department, and that a functioning staff of scientifically capable personnel be maintained for future emergencies, it is hoped that the Ballistic Research Laboratory will be adequately staffed in the future and that the new facilities required for the effective prosecution of ballistic research will continue to be provided.

FERROUS METALLURGICAL RESEARCH

By Lt. Colonel N. A. Matthews*
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Ferrous Metallurgical Research

OVER a period of many years the Laboratory of the Watertown Arsenal has become established as the agency of the Ordnance Department primarily responsible for research and development in the field of ferrous metallurgy. It exists today as one of the six laboratories of the Research and Development Service. The function of the Watertown Arsenal Laboratory may be described as the planning and conduct of the necessary programs of basic and technical research, principally in the field of ferrous metallurgy, which relate to the development, design, metallurgical engineering, and production of Ordnance materials and materiel.

The laboratory is housed principally in five adjacent buildings and is equipped with the most modern facilities for melting steel in small quantities and for analyzing its characteristics by essentially all of the physical, chemical, and metallurgical methods available today. Facilities range from those utilized for routine testing to the specially constructed devices required for evaluating the behavior of metals under the application of complex forces simulating those encountered in ordnance service.

There are three main operating divisions; Research, Metallurgical Engineering, and Testing, with auxiliary service organizations constituting the Property and Services Branch. The Research Division, consisting of five sections, has the primary responsibility of developing new knowledge and assembling basic information as to the factors affecting the behavior of metals and structural components used in Ordnance construction. These sections transcribe this information in such form that it can be applied by sections of the Metallurgical Engineering Division and other Ordnance agencies to effect improvements in the physical and metallurgical

* The statements or opinions in this article are those of the author and do not necessarily express the views of the Ordnance Department.

design of Ordnance materials or materiel. The Metallurgical Engineering Division is subdivided into sections responsible for the metallurgical phases of development of classes of Ordnance materiel such as guns, armor, and ammunition. In addition, there are two subdivisions concerned with the processing of steel, one of which studies melting and refining and the second of which carries out research and development programs in connection with welding processes as applied to the fabrication of ordnance. The sections of the Engineering Division have been largely occupied with development programs in connection with the improvements of standard weapons or the construction of new weapons and component items, but a considerable amount of research has also been conducted by their personnel.

The Testing Division performs the testing functions required by the Research and Metallurgical Engineering Divisions of the Laboratory and the Arsenal as a whole in connection with its production and procurement. Approximately one-half of its personnel conducts routine testing in connection with the Arsenal's production of guns, shell, and gun carriages.

The Ferrous Metallurgical Advisory Board is administered by the Watertown Arsenal Laboratory. This board, consisting largely of prominent industrial metallurgists, advised the Chief of Ordnance during the prewar years on matters of policy affecting the procurement specifications for ferrous materials. Early in this emergency subcommittees were organized under the Ferrous Board, dealing with critical classes of Ordnance materiel such as gun forgings, cast armor, and rolled armor, or special processes such as the welding of armor. These subcommittees have been the active agencies by which Ordnance personnel, in conjunction with representatives of industrial producing companies, have been able to effect coordination of technical development in connection with the metallurgical phases of the manufacture of these important items of ordnance materiel. Representatives of the Navy Department, the War Production Board, and the supervisor of the National Defense Research Committee projects involved in the committee's sphere of study, together with technical representatives of Allied countries and industrial companies of Canada, are included in the membership of these committees. Small subgroups, such as the Research and Specifications Groups, have been particularly effective in coordinating research activities and in revising drafts of new procurement specifications prepared by Ordnance agencies, prior to the submission of these drafts to the industry as a whole for concurrence. The subcommittees have served to introduce improvements in production resulting from research and development programs long before formal specification changes could be made and instituted. The activities of these subcommittees have been administered by personnel of the laboratory.

Many of the major applications of steel in the manufacture of ordnance involve strains which result in permanent deformation or fracture. In contrast to the design of commercial structures and machines wherein factors of safety are incorporated to minimize the likelihood of the initiation of plastic deformation, such items as projectiles, armor, and certain regions in gun barrels are expected to undergo considerable plastic deformation without rupture. The ordnance engineer in these cases is interested primarily in the behavior of the metal in the plastic state and, in the case of projectiles and armor, at high values of strain. In addition, extremely high strain rates are involved in conjunction with multi-axial stress applications which require inherent characteristics in the metal for successful service which are not demanded by the usual conditions of service stresses within the elastic strength of a material.

Modern war demands the utmost in mobility of ordnance materiel. This tactical doctrine is reflected in the great efforts which have been made during this emergency to develop weapons possessing a maximum combination of destructive effect and mobility. In order to achieve the desired mobility it has been necessary to develop materials of construction of higher strength. At the same time, these materials must retain superior structural dependability. In some applications of steel there are no factors of safety inasmuch as the design of an armored vehicle, for instance, is predicated upon a compromise among protection, mobility, and firepower. If the ultimate in protection is not realized from the unit weight of armor carried, a needless sacrifice has been made in some other desired characteristic.

Thus the ordnance problem in ferrous metallurgy is to develop a more complete understanding of the plastic flow and rupture properties required in steels to confer the optimum resistance to the stresses involved in a specific applica-

FIG. 1. Assembled apparatus for automatic tensile test recording. This operates in conjunction with standard mechanically loaded tensile testing machine.

tion and the means by which these properties may be most efficiently obtained. And yet, these results must be achieved during wartime on products which require great tonnages of steel. The corollary to the problem results when it becomes desirable to capitalize on the knowledge developed by incorporating into procurement specifications the controls which will insure a better gun, vehicle, or other ordnance item. The latter phase, under the pressure of production, is often the more difficult.

One of the stumbling blocks to a more scientific specification of materials for ordnance construction has been a lack of understanding of the factors which influence the mechanical behavior or the plastic flow and rupture of steels. Early attempts to understand phenomena observed in the penetration of armor indicated the necessity for investigating the effects of metallurgical factors and the variables of temperature and strain rate upon the flow and fracture stress curves for steel. As a result of investigations it was postulated that every metal has, at least in concept, a fracture stress and a flow stress. This work resulted in the establishment of a quantitative equivalence between the effects of strain rate and temperature on the behavior of steels. This concept has permitted the evaluation of the effect of strain rate on the behavior of steel as a function of metallurgical variables. Elaborate mechanical-electronic equipment was devised for this research which makes it possible to determine simply the instantaneous relationship between stress and strain throughout the period of deformation of tensile specimens at temperatures as low as that of liquid nitrogen (−190°C). The recording apparatus utilized in this equipment is shown in Fig. 1. Rationalization of the previously observed fact that the tempered martensitic structure is optimum for severe service applications such as armor, guns, and projectiles has been secured through these studies. It has been demonstrated that the tempered martensitic structure, as contrasted to structures involving preferred orientations of carbide, is associated with a fracture stress behavior which, in relation to flow stress, is comparatively unaffected by adverse conditions such as high strain rates, low temperatures, and multi-axial stress applications which tend to lead to brittle failure. Steels which have structures involving preferred orientations of carbide develop increasing fracture stress with increasing strain as a result of the reorientation of carbide during deformation, so that brittle failure is much more likely to occur because of the decreasing spread between flow and fracture stress caused by low temperatures, high strain rates, or transverse restraint to deformation. The schematic effects of these variables on the flow and fracture curves for a typical tempered martensitic and pearlitic structure are shown in Fig. 2.

Additional research has involved a complete evaluation of the significance of the notched-bar impact test and the effect of metallurgical variables on the performance of steel in this test, together with the interrelation between flow and fracture properties as determined by tensile and impact tests. The superiority of the tempered martensitic structure in steel for critical ordnance applications was again clearly demonstrated.

More recently, with the recognition by engineering sections of the laboratory that temper brittleness was a factor in alloy steels limiting the maximum combination of strength and toughness which can be attained in heavy sections, a concentrated effort has been made to arrive at a complete understanding of the nature of the reaction and its effect upon the properties of steel. Temper brittleness is a transformation phenomenon involving the precipitation of a minute quantity of a compound at grain boundaries which results in embrittlement of the steel. Research is presently under way designed to establish the identity of the constituent which causes the difficulty.

Present efforts of personnel of the Physical Metallurgy Section are being directed towards the acquisition of the fundamental information which will make possible the synthesis of steels for fully quenched parts of any type. By applying factors for the hardenability effect of each element and considering section size, together with the problem of carbon content and its effect upon quench cracking susceptibility, it is anticipated that the optimum chemical composition can be calculated for the manufacture of a given part.

With the understanding of the effects of variables upon plastic flow and fracture in steels, the Metallurgical Physics Section approached the problem of the interaction between projectiles and armor. Through scale-model firings in caliber .30 size with model artillery-type projectiles, wherein absolute uniformity and optimum quality could be achieved in both the armor and projectiles, studies have been completed which demonstrate the effect of projectile and armor variables and the fundamentals of the action of armor-piercing caps on projectile behavior. The phenomenon of shatter in projectiles has been investigated completely and the mechanism explained. The stresses causing transverse fracture in the cylindrical portion of armor-piercing projectiles have been analyzed and the characteristic in steels which affects performance in this respect has been determined. The qualities required for the optimum performance of armor-piercing projectiles have been established and progress has already been made in achieving improved performance in production projectiles of artillery sizes through the application of these principles.

The Metallurgical Physics Section has more recently devoted study to the mechanisms of the transformations in steel, in the belief that with a more complete understanding of these phenomena it should be possible to promote more rationally those transformations which are desirable and inhibit those which lead to inferior properties. It has been established that alloying elements affect the rate of transformation to pearlite by rendering ineffective the sites within the lattice which are capable of nucleating the reaction. By considering the free energy relationships involved in the transformations to bainite in steels, generalizations have been made which are consistent with the limited experimental data which are available. Thus the constants which govern the effects upon the rates of transformation to pearlite and bainite have been determined for the individual alloying elements.

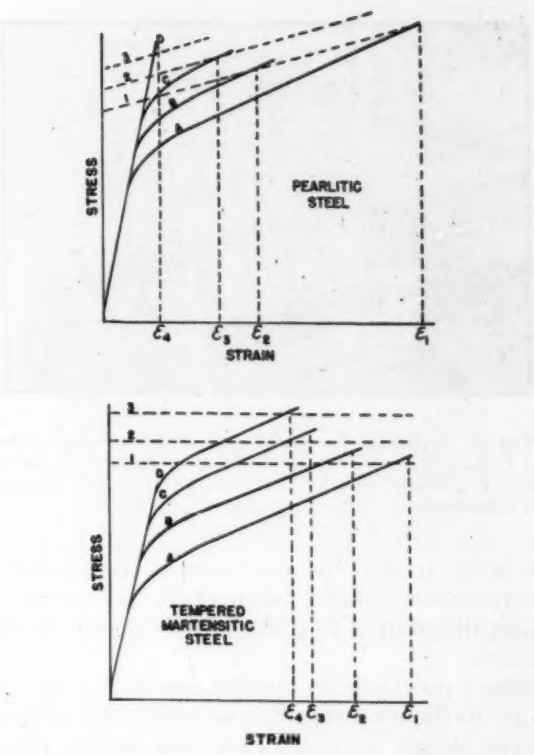

FIG. 2. Difference in effects of strain rate, temperature and stress concentrations (notches) on mechanical behavior of steels of typical structures. – – – – fracture curves, ——— flow curves, (1) (*A*) slow tensile test, 20°C, (1) (*B*) slow notched bar test 20°C, (2) (*C*) notched bar impact test, 20°C, (3) (*D*) notched bar impact test, low temperature.

A survey of the thermodynamics of the martensite reaction completed the study on phase transformations. It was found that the effects of the individual alloying elements on the temperatures of beginning and ending of the martensite range are in the same relation as their effects upon the bainite transformation.

Research by the Applied Mechanics Section has applied electrical strain gauges to the measurement of strains in guns under firing conditions. Out of this work has developed an appreciation of the importance of the pressure exerted by the rotating band upon the strains induced in a gun tube. Laboratory methods have been devised for determining the comparative merits of designs of rotating bands or of details of gun tube construction. These tests involve static pushing of projectiles through the bores of guns and are performed with the use of recording and loading apparatus of the type illustrated in Fig. 3. Special strain gauges have been developed which

FIG. 3. Apparatus for pushing shell through gun tubes. (*A*) Gun. (*B*) Push rod. (*C*) Testing machine. (*D*) Bridge unit. (*E*) Strain recorder. (*F*) Chart drive. (*G*) Fixture. (*H*) Strain gage. (*J*) Strain recorder. (*K*) Shell.

are being applied to experimental gun carriages to determine where weight may be saved or better distributed to effect improvements in the designs.

Other programs in applied mechanics are devoted to the mathematical solutions of problems in the design of gun tubes and breech rings. Information is being accumulated by which engineers can more accurately specify designs to resist anticipated service stresses in critical ordnance parts. The mathematical analyses of elastic and elastic-plastic problems are, in general, based upon experimental data obtained from strain records of models or full scale assemblies or by the photoelastic techniques which have been developed.

The Powder Metallurgy Section has been primarily involved with the determination of the fundamental effects of variables such as method of manufacture of metallic powder, particle size distribution, sintering temperatures, and compacting conditions upon the mechanical properties of parts made from powdered metals. This information has been utilized in the preparation of a series of specifications covering the procurement of parts to be made by powder metallurgy. Progress has been made in producing compacts with more superior combinations of strength and ductility than are commercially available.

The Testing Methods Section of the Research Division has been concerned with the preparation of inspection manuals and the preparation and coordination of the standards for the radiographic inspection of ordnance castings and weldments. One important activity involved the development of the standards and the preparation of drafts of specifications to govern the radiographic inspection of cast armor. The introduction of radiography has promoted a material improvement in the average quality of cast armor by insuring a satisfactory degree of solidity through the section thickness.

Early in 1941 the Armor Section of the Metallurgical Engineering Division recognized that the ballistic performance of armor was controlled by its structure rather than by chemical composition. Experiments carried out on the basis of this premise demonstrated that armor of excellent quality could be produced from steels of much lower strategic alloy content than were common at that time. When the demand to conserve alloys developed early in 1942, this information provided the basis by which the cast and rolled armor industries, through cooperative efforts coordinated by the Subcommittees on Cast and Rolled Armor, accomplished complete transition to low alloy types of steel within five months. Undoubtedly it can be said that in no other critical class of material were such effective conservation measures achieved.

Subsequent efforts in connection with armor have involved studies which first determined the essential characteristics of armor and then proceeded to develop simple tests by which these qualities can be controlled. These developments have been so successful that it is now possible to control quality and uniformity more adequately by these tests than by ballistic firing tests. One test of particular interest is the *Fibre Fracture Test* which was developed to control the resistance of armor to brittle failure. It involves fracturing a properly notched, small piece of the armor after heat treatment and observing the fractured surface. A ductile, high energy fracture has an unmistakable dull, fibrous appearance in contrast to the crystalline appearance of the brittle fracture.

Considerable research has been conducted to determine the characteristics required in thin armor designed to afford protection against shell, grenade, and bomb fragments. The results of these programs have been applied to the preparation of specifications covering the steel or other materials used for helmets and body armor and for armor to be installed in aircraft to protect vital installations and personnel from the destructive effects of the fragments from bursting projectiles.

Research in metal-arc welding has been devoted to an analysis of the metallurgical variables

which must be understood to effect improvements in the welding process as applied to the fabrication of critical ordnance materiel such as the armored structures of combat vehicles. The cause of underbead cracking, formerly one of the most severe limitations to the welding of hardenable steels, has been found to be hydrogen. This hydrogen dissolves in the molten metal during deposition and later diffuses into the martensitic zone of the heat affected base metal and causes cracks. Means have now been developed which minimize the absorption of hydrogen during welding, and the path is now clear to achieve tremendous progress in the welding of alloy steels with high strengths and using electrodes of low cost. One of the more spectacular of these results is shown in Fig. 4 which illustrates the extent of plastic deformation resulting from high velocity ballistic impacts which can take place in welded joints in armor plate of .40 percent carbon prepared with ferritic electrodes. Steels of such carbon contents could not be welded with the electrodes commercially available three years ago without considerable cracking, which would prevent satisfactory performance. These developments will have a great effect on the progress which is made in applying high strength steels to the fabrication of mobile equipment. Programs are now under way which, capitalizing on this knowledge, will apply steels of greatly increased yield strengths to the fabrication of such mobile equipment. Before the use of high strength materials could be contemplated, however, it was necessary that the causes of brittle failures in steel be thoroughly understood and methods developed by which control could be exercised over the properties of steel procured for these applications.

Research is presently in progress to investigate the response of different steels to the complex thermal cycles resulting from the preparation of multiple pass welded joints. Results obtained to date indicate that wide differences in the properties of steels after these treatments may be attributed to steel making variables. These studies have demonstrated that much fundamental research is required in the field of process metallurgy before real progress can be made in improving the quality of steels for the manufacture of critical ordnance materiel.

The developments carried out by the Process Metallurgy Section have been chiefly associated with problems involved in the manufacture of cannon tubes by the centrifugal casting process

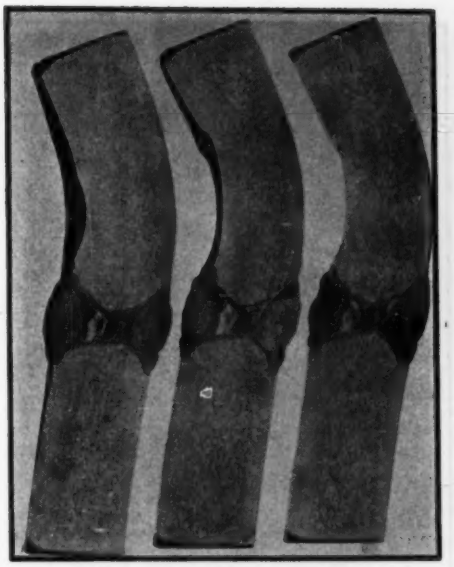

FIG. 4. Welds in .40 percent carbon armor plate made with hydrogen-controlled ferritic electrodes. Note plastic deformation which has taken place under ballistic impacts.

as practiced at this arsenal. A newly designed casting machine has been in operation for some time which represents the latest developments in the art. This machine incorporates such flexibility that research programs may be conducted to investigate factors such as speed of rotation, mold cooling conditions, deoxidation practice, and the variables which influence the formation of casting defects. Additional studies have been conducted on methods of improving quenching efficiency in the heat treatment of gun tubes and innovations in procedure have been developed which materially reduce heat treating costs.

The Carriage and Vehicle Branch of the laboratory has been concerned with innumerable problems associated with the materials utilized and the designs of parts for the construction and lubrication of gun carriages and the structural elements of armored vehicles. Its activities have been devoted in the main to investigations of manufacturing deficiencies. The causes of the short life of recoil mechanisms for gun mounts of some designs have been established and corrective measures have been instituted. Design studies have been made which are expected to result in a greatly increased life for recoil mechanisms and which will unquestionably simplify the manufacture and maintenance of these important elements of an artillery mount. Considerable assistance has been rendered to agencies of the Office, Chief of Ordnance in connection

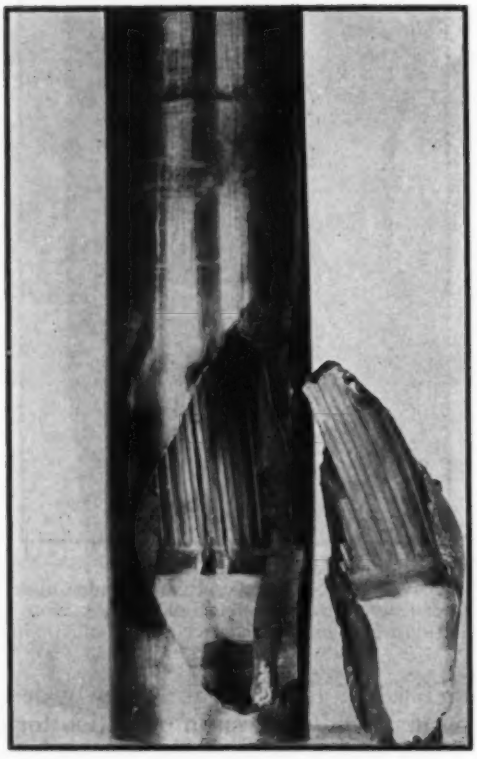

FIG. 5. Brittle failure in 75-mm highly stressed gun tube associated with poor toughness characteristics.

with their material and design problems associated with the production of numerous ordnance items.

The Gun Branch is responsible for studies in connection with the metallurgical factors affecting the behavior of guns, breech rings, and breech blocks and also performs research to determine the factors which limit the life of guns through mechanical or physical-chemical effects at the bore surface associated with the action of the products of combustion of the propellent powders. Its personnel administer the affairs of the Subcommittee on Gun Forgings. One of its most important contributions has been the solution of the metallurgical problems involved in the manufacture of gun tubes of high yield strength. It was confirmed that the tempered martensitic structure was optimum to achieve the desired behavior of guns of new design which were extremely highly stressed as a result of efforts to conserve weight in the armament for armored vehicles and aircraft. Manufacturing procedures and concepts were altered throughout the gun forging industry to produce this materiel satisfactorily. The type of failure in proof firing associated with a poorly heat treated, highly stressed gun is illustrated in Fig. 5. These difficulties have now been overcome and much more efficient gun designs have resulted.

The intricacies of the erosion problem in guns are not yet understood adequately. Progress in the design of guns with respect to increases in muzzle velocities and rate of fire has been so rapid that the erosion problem has changed constantly. The phenomenon of progressive stress damage, which may lead to premature failure, has been explained and the means for minimizing its effects upon the life of highly stressed gun tubes have been established. This effect is now recognized as a major factor to be considered in the metallurgical and physical considerations involved in the design of highly stressed guns.

The contributions of the laboratory to the Ordnance program result, in general, from changes which are made in procurement specifications. The work which is conducted on specifications may, therefore, be considered of primary importance. The Specifications Section is the coordinating agency for the laboratory and works closely with other sections in the preparation of drafts of new specifications, which in many cases incorporate the results of research and development programs.

The Watertown Arsenal Laboratory has been particularly fortunate in the capable personnel with which it has been staffed during the emergency and in the vision on the part of the personnel of the Ordnance Department who establish the policies governing its activities. Its personnel have acted as War Department liaison on many projects carried out under the auspices of the National Defense Research Committee. Members of its staff have continuously served as representatives of the Ordnance or War Department on technical committees of national organizations such as the American Welding Society, the American Society for Testing Materials, the Society of Automotive Engineers, and the American Society of Mechanical Engineers. The laboratory has maintained close contact with other arsenals and the establishments of the War and Navy Departments engaged in allied activities.

The laboratory has performed numerous investigations of items of enemy ordnance materiel and the results have been reported to the agencies which can benefit to the greatest extent therefrom. The thinking of its personnel has been assisted by these studies and this in turn has

led to improvements in the equipment of this country.

The results of a considerable portion of the research conducted are generally applicable to the science of ferrous metallurgy. Much remains to be done; it is certain that within the last two years a maximum rate has been reached in the development of the fundamental principles which govern the proper selection and application of materials to ordnance construction.

The necessity for fundamental research in metallurgy for the development of superior ordnance materiel has been clearly established. The desirability of centering research in well-rounded laboratories has been clearly indicated. The engineer learns from the person engaged in research in his field. The research man, on the other hand, is guided in his thinking and his efforts may well be directed by factual information obtained by the engineer which enables him to generalize a theory. The theory must then be substantiated by experimental results which will justify a new concept which can, in turn, be applied broadly to the development of superior ordnance.

NON-FERROUS METALLURGICAL RESEARCH AT FRANKFORD ARSENAL

By Lt. Colonel C. H. Greenall
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THE Frankford Arsenal is charged, under the direction of the Chief of Ordnance, with the establishment of methods of production and manufacture of small arms ammunition, artillery ammunition components, and fire control instruments. It is also responsible for conducting research, design and development of standards, and the establishment of newer types of weapons as directed. These functions require the utilization of a wide variety of non-ferrous metals and alloys, and as a result, Frankford Arsenal has been designated as the Non-Ferrous Research Center of the Ordnance Department.

There are three main manufacturing divisions at Frankford Arsenal producing complete rounds of small arms ammunition, various components of artillery ammunition, and fire control instruments. The Fire Control Design Division designs and develops new fire control materiel, and the Laboratory Division conducts research and development work and provides control and assistance to the manufacturing divisions of the Arsenal in the solution of problems as they occur. In times of peace, the Arsenal maintains up-to-date production facilities operating continuously, thereby furnishing materiel to meet peacetime needs and supplying the early demands of war. At the outbreak of an emergency requiring enormous quantities of war materiel, the experience and procedures are made available to industry and the Arsenal functions as a control and advisory center maintaining its activities in developing new and improving current types of materiel.

Much of the research and development work at Frankford Arsenal on non-ferrous materials is effected either directly or indirectly by the Laboratory Division, which is organized to handle non-ferrous metallurgical problems of any type concerned with functioning of Ordnance materiel. Problems involving non-ferrous research are involved in ballistics, electronics, chemistry, explosives, mechanical design and construction, finishing and corrosion, and metallurgy. All of these fields are explored by the various sections of the Laboratory Division working as a team. From this coordinated effort have come developments such as projectiles which will efficiently penetrate the enemy's armor through use of a more efficient ballistic cap or rotating band of a non-ferrous type, or they may be hidden as an improvement in cartridge metal to minimize the tendency of this metal to season crack, thereby obtaining longer life of the ammunition.

Owing to the nature of the work and the magnitude of the problems involved, it was recognized by the Ordnance Department that it would be necessary to obtain assistance from both industry and educational institutions. In accordance with this, the Non-Ferrous Metallurgical Advisory Board was organized by the Ordnance Department in 1940. This Board consists of 17 representatives of the Army, Navy, universities, and industry, and as the occasion arises, it reviews data, reports, and specifications.

In many cases the facilities of the Arsenal are supplemented by contacts with universities and industry, either directly or through the National Defense Research Committee. Later in this article specific examples of results obtained through these contracts will be discussed. Needless to say, the utilization of technical personnel and equipment of these organizations has been an invaluable link in the Industry-Ordnance team.

The largest field of non-ferrous research in the Laboratory Division is that of copper and copper base alloys. Physical and mechanical properties of pure copper and its alloys in the cast, wrought,

and powdered conditions are constantly under investigation. Data on workability, stress relief anneal, recrystallization, stress relaxation, high speed deformation, and internal friction characteristics under various conditions of test are obtained. X-ray and gamma-ray studies, as well as metallographic studies of structures and methods of preparation are fields of constant investigation. Castability, fluidity, strength, aging, heat treatment, and other characteristics of the bronzes, brasses, and related special alloys are studied.

One of the most serious problems involved in the storage of ammunition over a period of time has been that of stress corrosion cracking, that is, season cracking of the brass. In the period between World War I and World War II several investigations were conducted to determine the cause of season cracking in brass cartridge cases and preventive practices were established. Of the practices employed, probably the stress relief anneal and the mouth anneal of the cartridge case have been the most beneficial. The mechanism of season cracking has eluded, however, all investigators and even up to the present time has not been definitely established.

Early in 1940 an expanded program of investigation of season cracking was undertaken to study the source of this phenomenon in cartridge brass. One of the first steps was a standardization of the mercurous nitrate test which is still used to test for season cracking tendencies. Based upon the work originated at Frankford Arsenal,[1,2] the mercurous nitrate test was standardized by the American Society for Testing Materials in cooperation with the Ordnance Department. Simultaneously, the source of corrosive atmospheres in cartridges was investigated and data on smokeless powder, previously considered to be free from suspicion, indicated that this was a major source of corrosive agents;[3] detailed studies have been made of the cracking power of amines (6).[4] Another program was initiated in which the residual stresses in cartridge cases found to be responsible for season cracking tendencies, were studied with the cooperation of the Case School of Applied Science. The effect of such factors as die angle, drawing speed, grain size, rate of reduction, and distribution of sink and ironing operations on resultant distribution of stresses was investigated.

In connection with the program on stress corrosion cracking, Frankford Arsenal utilized the x-ray diffraction method of measuring residual stress. This method was proposed in 1925 by Lester and Aborn[5] at Watertown Arsenal. Because of limitations in the equipment available at that time, however, these investigators were unable to obtain sufficient sensitivity to make the method feasible; with the development of x-ray tubes emitting softer radiation and the use of the back reflection camera, the x-ray measurement of residual stress became more practical. In 1941 a preliminary study at Frankford Arsenal indicated that, although diffuse diffraction lines from cold worked brass caused considerable difficulty, the technique showed definite promise. Upon the opening of hostilities the experimental work was transferred from the Arsenal through NDRC to Lehigh University, where the work has been carried on in close cooperation with the Arsenal. Through this cooperative effort, the method has been developed to such an extent that it is now being used to determine the effect of changes in manufacturing processes on the residual stress distributions in small arms cartridge cases.

There has been a serious need emphasized by the shortage of brass which necessitated reworking fired cases, for a rapid and reliable test to detect the presence of stress corrosion cracks in the side wall of fired brass artillery cartridge cases. Firing splits cases have been ascribed to the presence of stress corrosion cracks. Stress corrosion cracks in side walls of cases do not cause firing splits unless these cracks extend through a considerable fraction of the wall thickness. Only those cases in which the cracks are deep enough to give rise to splitting in firing need be discarded. Equipment for carrying out a damping capacity test at a large stress amplitude permits solution of this problem. In order that the inspection device may be used on a production line, it is made semi-automatic and sufficiently rapid in operation to handle 600 or 700 cases per hour.

A study also was begun of the effect of alloy compositions on the tendency to season crack. Industry was called upon, and the New Jersey

[1] H. Rosenthal and A. L. Jamieson, "Mercury Cracking Test, Procedure and Control," ASTM 41, p. 897 (1941).
[2] H. P. Croft, "Influence of External Stresses on Tendency of Brass Wires to Stress Corrosion Crack as Indicated by the Mercurous Nitrate Test," ASTM 41, p. 905 (1941).
[3] J. W. Mitchell, "The Role of Smokeless Powder in the Season Cracking of Small Arms Ammunition," AIME-ASTM Symposium on Stress Corrosion Cracking (1944).
[4] H. Rosenthal and A. L. Jamieson, "Stress Corrosion Cracking of 70/30 Brass by Amines," AIME 156, 212–221 (1944).
[5] H. H. Lester and R. H. Aborn, Army Ordnance, 6, 120, 200, 283, 363 (1925–1926).

Zinc Company, who assisted in this investigation, prepared the purest brass known to exist. Studies of single crystal and polycrystalline characteristics of 70/30 brass in mercurous nitrate and ammonia environments were also made. The relatively old but undeveloped ammonia test for stress corrosion cracking tendencies was investigated. Two distinctive methods of ammonia test were developed.[6,7] The aqua-ammonia test has been thoroughly investigated while gaseous ammonia test methods, which have much more flexibility and a great number of variables, were partially investigated.

Several special techniques used for studying the phenomenon of season cracking have been investigated in conjunction with the Aluminum Company of America. Solution potentials of the grain boundaries and the grain material have been studied from the viewpoint of the electrochemical theory of the phenomenon.

Damping characteristics of 70/30 brass and the variations encountered have likewise been of great assistance in understanding the mechanism of season cracking. The activity of Frankford Arsenal in the stress corrosion field is illustrated by its participation[8–11] in the recent AIME–ASTM Symposium on Stress Corrosion Cracking, at which time the Ordnance Department attempted to gather all information on this subject into one volume. (Figure 1.)

The use of light alloys in Ordnance equipment has expanded considerably during the last five years, as a consequence of the necessity for saving weight, not only for aircraft applications, but for ground troops. A considerable weight saving can be effected by the use of aluminum alloy cartridge cases and primer components for ammunition. In addition, aluminum alloys are being investigated for use in body armor to protect flying personnel against fragments, and in thicker armor for protection of aircraft structures.

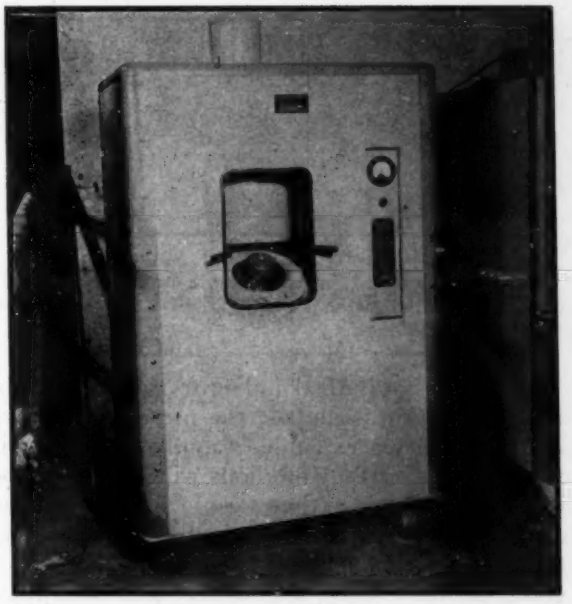

FIG. 1. The Frankford Arsenal damping capacity testing device for artillery brass cartridge cases.

Aluminum primer components are being used in experimental ammunition in order to insure stability of certain priming compositions which are less corrosive than the current standard types.

The use of aluminum alloys in permanent mold or sand castings for fire control instruments has been developed and various heat treatments have been investigated for the development of appropriate physical properties. Recommendations have been made for aluminum and magnesium alloys in rocket launchers and fuze parts. Frankford Arsenal is now assembling a large amount of information on light alloys to meet the growing demands for greater mobility of equipment in all fields of Ordnance.

One method of attack on the problem of stress-corrosion cracking of brass was the interposition of a resin film between the corrosive agent and the metal. A search was made through various types of thermosetting and thermoplastic resin formulations until one was found which was impervious to ammonia—an unmodified heat reactive phenolformaldehyde varnish. It was shown that a continuous film of this resin would effectively prevent season cracking. This study of synthetic resin finishes led to an accumulation of data on the resins, their plasticizers and modifiers which were used extensively in other applications of organic finishes which arose during the war years.

[6] H. Rosenthal and A. L. Jamieson, "An Aqua Ammonia Test," AIME-ASTM Symposium on Stress Corrosion Cracking (1944).

[7] G. Edmunds, E. A. Anderson, and R. K. Waring, "Ammonia and Mercury Stress Cracking Tests for Brass," AIME-ASTM Symposium on Stress Corrosion Cracking (1944).

[8] H. Rosenthal and J. Mazia, "Residual Stresses in Caliber .30 Cartridge Cases," AIME-ASTM Symposium on Stress Corrosion Cracking (1944).

[9] T. A. Read, H. Fusfeld and S. W. Kitchen, "Sonic Test for Cracks," AIME-ASTM Symposium on Stress Corrosion Cracking (1944).

[10] H. Gisser, "Protective Resin Films on Cartridge Brass," AIME-ASTM Symposium on Stress Corrosion Cracking (1944).

[11] T. A. Read, J. B. Reed and H. Rosenthal, "Mechanism of Season Cracking," AIME-ASTM Symposium on Stress Corrosion Cracking (1944).

FIG. 2. High speed x-ray picture of bullet immediately after leaving muzzle of gun. Note that the jacket has started to strip.

As a result of critical and strategic shortages of many non-ferrous metals, the use of zinc alloys and zinc plating expanded rapidly. However, it was soon found that methods would have to be developed to reduce the rate of corrosion of zinc and minimize "blooming" of this metal with its attendant voluminous corrosion products. Thus a comprehensive study was undertaken of supplemental chemical, electrochemical, and organic protective coatings for zinc surfaces. The Electrochemical Section of the National Bureau of Standards cooperated in this work.

In connection with optical instrument manufacturing, an investigation was conducted of methods of producing black finishes on aluminum, zinc, copper, and nickel alloys. Black dyed anodic finishes of wrought and sand cast alloys were studied on coatings produced both in sulphuric and chromic acid electrolytes.

Many special problems have arisen involving the moisture proofing and fungus proofing of materiel. Mycological studies have been made of many of the materials used to manufacture Artillery and Fire Control materiel, with a view toward choosing constructional materials of a fungistatic nature. In many cases this was not possible and research was required to find a suitable fungicidal or fungistatic protective finish.

Problems related to the long term storage of equipment are being actively studied. It is particularly important to develop methods whereby materiel may be preserved for a long period in a state of readiness for active use. The testing of spray formed plastic films, dehumidification, inert gas atmospheres, and long range applicability of lubricants and rust preventives have been the major part of this investigation.

The war has seen the development of precision casting of non-ferrous metals as a production method for the forming of small intricately shaped parts of various alloys for Ordnance materiel. The method is an adaptation of the age-old "lost wax" technique, by which bronze statues and art works were cast and which was adapted more recently by dentists for making inlays and bridges. The modern technique consists of casting a wax pattern in a suitable mold, mounting the wax patterns on wax sprues and gates, surrounding the wax assembly with liquid plaster, burning out the wax after the plaster has hardened, and finally casting the metal in the cavity thus formed, usually employing centrifugal force for injection of the molten metal into the ceramic mold.

Although many applications have been found and many parts have been successfully produced, very little data are available on the non-ferrous alloys which may be cast, or the properties developed in the castings. In view of the growing importance of this field, the Laboratory Division has undertaken a metallurgical study of the properties of precision cast alloys in the copper base, aluminum base, zinc base, and magnesium base systems.

Heavy demands for copper and zinc led to a study of substitute materials. Research programs were, therefore, carried out on brass and steel with a view toward producing a satisfactory steel cartridge case. This involved the selection of a non-critical steel which could be drawn into the desired shape and which would develop the required mechanical properties. Initial work revealed that medium carbon steels could be satisfactorily drawn and that suitable mechanical properties could be developed by quench hardening.

In the manufacture of small arms steel cartridge cases, it therefore became necessary for the non-ferrous metallurgists to acquaint themselves with the problems involved in producing steel cases. Pilot lines were set up for the production of caliber .30 cartridge cases and every operation for the production of a finished cartridge case was critically investigated. Engineering services were likewise furnished the artillery steel cartridge case manufacturers in setting up procedures and investigating production difficulties and ballistic failures.

The loss of the Far East source of tin necessitated the search for substitute materials for bearings and solders. A serious problem encountered in the production of ammunition, for example, was that approximately .3 pound of 70 percent tin–30 percent lead solder was consumed in soldering each ammunition box liner. Alloys of tin and lead with varying percentages of tin from

10 percent to 70 percent were investigated, as well as tinless solders of the lead silver type containing either arsenic, calcium, antimony, or bismuth. The use of these new solders necessitated the investigation of various types of sheet metal coatings for the steel so as to permit satisfactory soldering.

For bearing applications ten lead base alloys representing a wide variation in composition were studied in comparison with tin base reference alloys. The tests indicated that in babbitted bearings with a white metal layer .005" in thickness or less, all of the lead base alloys investigated were superior to the standard reference alloys previously employed. In non-supported bearings or bearings with thicker linings it appeared that the tin base alloys were superior to the lead base alloys with respect to load sustaining qualities, although certain of the lead base alloys closely approached the qualities of the tin base alloys.

It would not be proper to close this article without a brief mention of some of the other work being carried on in cooperation with the non-ferrous metallurgists. The equipment and experience normally employed on problems other than non-ferrous are at the service of the metallurgists. For example, the Mechanical Engineering Section of the Laboratory Division has complete equipment for the manufacture of complete rounds of small arms ammunition and artillery components; these facilities are used for producing experimental cases from special brass compositions which the metallurgists have developed, or for improving the technique of manufacture by reducing the number of draws, reducing the weight of the finished case, or utilizing remelted scrap brass. Primer components are manufactured with special materials, tolerances and properties, assembled and tested in order to determine the effects of controlled variables or sensitivity and stability. Another example is the development of the shell deflection gauge, which has made possible the study of rotating bands of various alloys under actual firing conditions.

The work of the Ballistics Section is likewise related to that of the metallurgists. In this Section is included high speed x-ray equipment[12] capable of making an exposure of one millionth of a second, by means of which the behavior of various non-ferrous jackets for bullets has been studied under various firing pressures and velocities. (See Fig. 2.) High speed motion pictures employing speeds up to 10,000 frames per second are used in studying the dynamic regulation of mechanical time fuzes, as well as the functioning of jet propelled projectiles against armor. Experimental rifle barrels which have been chromium plated, made from special wear resistant non-ferrous alloys, or specially heat treated, are exhaustively tested with various types of ammunition. Constantly increasing demands for high velocity and longer service life of weapons have required the utmost coordination between the developments of the physicists, mechanical engineers, powder and explosive chemists, and metallurgists. (See Fig. 3.)

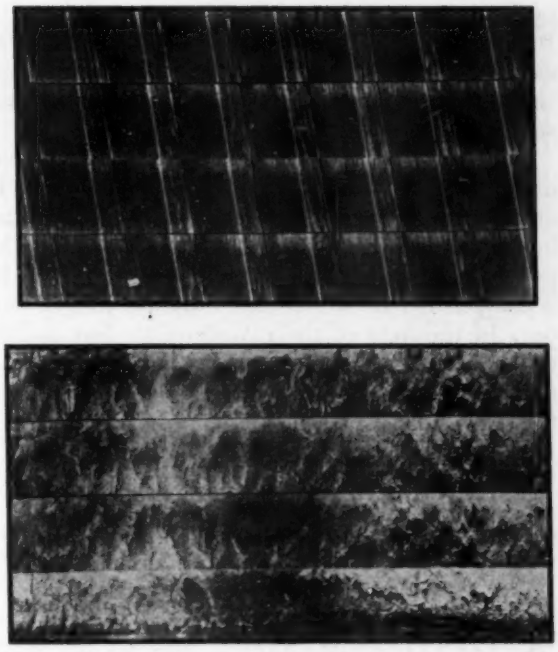

FIG. 3. Photographs of the bore surface of a small arms barrel taken with a Borescope camera. Top shows an early stage in the life of the barrel. Bottom shows the extreme erosion produced by firing the barrel well beyond its useful service life.

In the field of the Chemical Section is included the study of lubricants used in fabricating non-ferrous alloys. Increased production of a wide variety of components at greatly reduced costs has been a direct benefit derived from research in drawing and machining lubricants. The complex association of different alloys in fire control instruments, coupled with severe service and storage conditions, has placed exacting demands on the lubricants used; here again, research work in the Chemical Section has resulted in better

[12] C. M. Slack and E. R. Thilo, "Field Emission Applied to Ultra-Speed X-ray Technique," Proc. Nat. Electronics Conference, 1, 447–456 (1944).

performance and longer life of these instruments. In addition, the Chemical Section has conducted extensive studies on powdered metals, particularly those used in pyrotechnic compositions, such as primers, tracers, and incendiaries.

Summarizing, it should be pointed out that only a few examples of metallurgical research, and research in other fields at Frankford Arsenal have been mentioned in this brief article. The progress which has been made and which will be accomplished in the future may be judged not only in the field of the metallurgist, but also in that of the physicist, chemist, corrosionist, and mechanical engineer with which the activities of the metallurgist are so indissolubly linked.

RESEARCH AND DEVELOPMENT, MILITARY EXPLOSIVES AND PROPELLANTS

By Colonel Miles W. Kresge
Chief, Technical Group, Picatinny Arsenal

A CONTINUING project was set up years ago in the Picatinny Arsenal Laboratory (Fig. 1) to evaluate explosives submitted, without solicitation, by civilian agencies. One such explosive culled from among the many submitted, as a typical representative specimen, consisted of a mushy mixture of dried blood, bone meal, turpentine, and sodium chlorate. The evaluation of these proposed explosives has grown into an activity of some magnitude despite the fact that in almost every instance a trained explosive chemist could dismiss at a glance these formulas as being without value as military explosives. Instead, long and elaborate tests must often be performed before the suggestor (and his backers) is satisfied that his "explosive" has been given the serious consideration it deserves. I cannot recall a single one out of the many formulas submitted over a period of years that has had value as a military explosive.

The foregoing element in the activities of an outstanding government establishment devoted to research and development of propellent powders and explosives is selected as an introduction to this article, not with any thought of belittling the good intentions of patriotic suggestors but to emphasize how general and widespread is the lack of understanding of what is and must be involved in the research and development of military explosives.

The development of new explosive compounds suitable for military use is not an easy matter. To develop compounds that will be not only suitable but superior to known available explosives is a far more difficult task. The number of explosive compounds standardized for use in modern munitions is relatively small in spite of the fact that thousands of explosive compounds are known and many hundreds of them have been investigated for possible military applications. All propellants, high explosives, initial detonating agents, fuze powders, and primer compositions now standard in the Army involve the use of only 12 different explosive compounds.

Most of the explosive compounds used by the belligerents of this War have been known for many years. Nitrocellulose and nitroglycerin, the principal constituents of modern propellants, were studied and their properties generally known during the 19th century. Picric acid, TNT, ammonium picrate, and tetryl were also known as explosives prior to 1900. Of the more recently standardized high explosives, RDX and PETN were well known twenty years or more ago and the most recent one, Haleite, had been investigated for five years or more before its adoption. It is quite evident that there are very special requirements which an explosive must meet before it can be accepted for use. The difficulty which confronts the organization charged with the development of explosives results from the many requirements that an explosive must meet to fulfill the exacting demands of military ammunition.

Research on military explosives, considered broadly, is an organized directed effort to develop the most generally favorable explosive for each of the various specific military applications and involves research largely in chemistry, physics, and chemical engineering.

The first phase of this research, which is largely in the field of chemistry and more particularly organic chemistry, may be divided into two major activities: (1) the synthesis of new compounds, or formulation of new compositions,

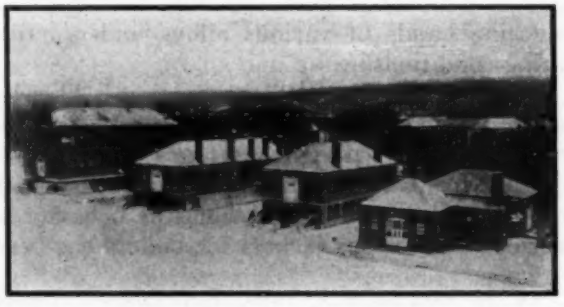

Fig. 1. The laboratory area, Picatinny Arsenal.

and a study of their essential properties; (2) studies of new methods for the preparation of standard explosives with a view to an improvement in their quality or simplification of the standard manufacturing procedures in order to reduce cost or increase production capacity of existing facilities.

The second phase involves the determination, by physical rather than chemical methods, of the explosive behavior of new compounds or compositions and the classification of these compounds with respect to their possible practical application; i.e., initial detonating agent, booster charges, fillers for shell or bombs, etc. Such work requires facilities not available in a chemical laboratory and because of the quantities of explosives involved is commonly carried out at testing stations or proving grounds.

The third phase comprises semi-plant or pilot plant studies of manufacturing processes, this including not only the production of the explosive in an acceptable state of purity but also the development of methods suitable for large scale handling and loading of the explosive. This phase is predominantly in the domain of chemical engineering.

Although the initial research work on processes for preparing explosives, the synthesis of new compounds and the formulation of new compositions are largely the field of the chemist, the determination of the explosive properties which permit prediction of the functioning characteristics in ammunition requires the services of the physical chemist and physicist. The measurement of explosive properties is a highly specialized field and presents many unusual problems because of the speed of explosive reactions and the hazard to personnel and equipment resulting from the inherent nature of the materials. In the first phase of the work on new compounds or compositions, it is necessary that the research chemist make preliminary tests to establish the general characteristics of the explosive. Thus, its sensitivity to ignition or detonation by impact, shock, friction, and heat must be determined. The rate of detonation or burning under various conditions, the energy and volume of gases released upon decomposition, and the stability or resistance to decomposition under various conditions of temperature and humidity are essential properties that must be evaluated before further investment of time and effort in the investigation is warranted.

With generally favorable results from such laboratory measurements the second phase of the study of the explosive is undertaken, the purpose being to determine more precisely the functioning characteristics required for specific applications. The instrumentation employed in this work is varied, in many cases highly complex. The fact that substantial charges of explosives are regularly used in such determinations makes necessary special facilities in the way of bombproof structures and elaborate precautions for the protection of personnel and the expensive equipment used. A description of the development of methods and instrumentation is a story in itself. It will suffice here to mention briefly some essential and typical measurements.

FIG. 2. Equipment employed in determining physical properties of propellent powders, showing specimen and extensometer at far end of machine and recording drum at near end.

The rate of detonation of a high explosive is an important property and is determined by means of a high speed rotating drum camera which photographs the streak of light which accompanies the detonation wave as it travels along the column of explosive (Fig. 2). Careful preparation of test pieces, involving the use of x-ray examination to insure absence of flaws, and technique of the highest precision in manipulating the equipment are employed to obtain extreme accuracy of results.

The burning rate of propellent powders and the duration of flash of illuminating shell, photoflash bombs, and fuze primers are representative of techniques in which the cathode-ray oscillograph is used in measuring small time intervals (Fig. 3).

Photometric and spectroscopic equipment are extensively used in establishing candle power

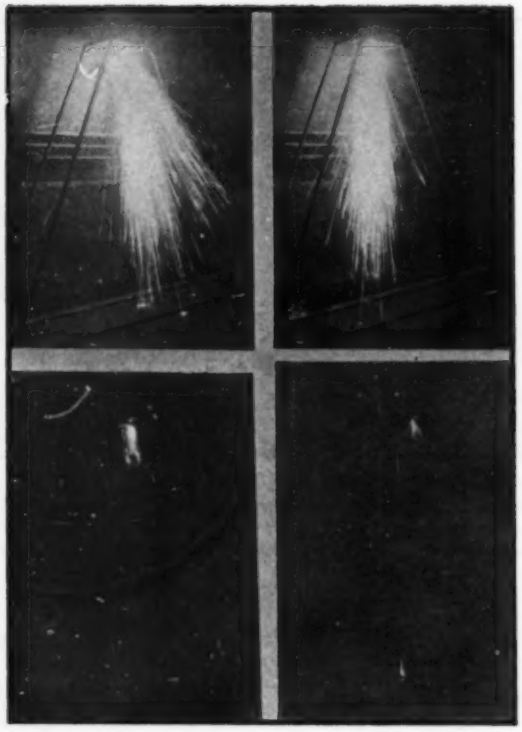

FIG. 3. Primer characteristics. Photographs of the flames from two types of primers are shown; top photographs illustrate an improved primer while the bottom ones show the small flame from an unsatisfactory type of primer. Firing and photographic conditions remained constant throughout the test.

and color standards for the light from pyrotechnic devices. Photoelectric cells and high speed photography are used in evaluating smoke and flash from weapons and devices.

The recently developed technique of flash radiography has been applied with considerable success to the investigation of the transient phenomena accompanying the functioning of explosives and explosive devices.

Numerous theoretical investigations have materially advanced the understanding of the mechanism of the explosive phenomena and the burning of propellent powders, and have resulted in establishing more precise definitions for such terms as explosion, detonation, and burning. The use of methods resulting from these investigations permits much more accurate prediction than was previously possible of the functioning characteristics of explosives when they are employed in ammunition.

When the chemist and physicist have established that an explosive offers distinct possibilities for military use, the question of its practicability from a production and loading standpoint arises. Many explosives have been known for years to offer great promise for military use when consideration is given only to power, brisance, or blast effect but have not been applied to ammunition because of limiting factors involved in the production, handling, and loading of the material or because of special difficulties in manufacture or in storage, transportation, and the handling of munitions in which such explosives might be loaded. The problems involved in this phase of the investigation of explosives require the services of the chemical engineer for proper treatment.

In pilot plant studies of manufacturing and loading processes, the details are established for economical production, and equipment is designed to permit maximum safety in the nitration, purification, and drying procedures commonly involved in the manufacture of explosives. Likewise, in the large scale loading of explosives in ammunition components, equipment design is all important so that the screening, melting, extrusion, pressing, or other operations in the loading plant are conducted with maximum efficiency and minimum hazard.

Some of the important contributions made in recent years by the chemical engineer in this third phase of research and development of explosives include complete plant layouts for the manufacture of the new explosives RDX and Haleite; several innovations in TNT and tetryl manufacture which increased the yield and reduced the cost of these explosives; the design and introduction of continuous melting units for TNT loading plants; development of manufacturing procedure, design of equipment, and layout of new plants for production of rocket propellants, trench mortar propellants, and new types of fuze powders. While the list could be extended, these examples of things accomplished indicate the important part the chemical engineer plays in the development of explosives.

It should be emphasized that a research organization whose principal activity is the development of military explosives is also concerned with many investigations of non-explosive materials that are required in the assembly of ammunition. Since these materials are often used in contact with explosives, it is necessary that the suitability of the materials for each specific purpose be established. The possibility of chemical reaction between the explosives and metals, coating ma-

terials, and gasket or other sealing materials must be determined and suitable materials developed if they are not already available. An outstanding research investigation of this type involved the development of a suitable cartridge cloth for use with all semi-fixed and separate loading propellent charges. Silk cloth had been used for this purpose until the present War when the supply of silk from the Orient was cut off. No delay whatever occurred in the loading program due to this situation, since substitute cloths had been established for each specific propellent charge and specifications prepared before 1940. This investigation was initiated in 1923 and successfully completed by the time the application of substitute cloths was necessary.

If there is any doubt regarding the effectiveness and practical value, from the standpoint of national security, of the research work on explosives and related materials as carried out by the Ordnance Department during the peace time years, it can be stated, as a matter of fact, that the saving effected to date in the procurement of the substitute cartridge cloth as compared to the cost of silk, if it had been obtainable, has exceeded many times the total amount of funds allotted by the War Department for all research and development work on explosives during the 20-year period between the Wars.

It has been the policy and practice in the conduct of the research work of the Ordnance Department to keep abreast of the advances made in the chemical industry as a whole in order to make use of any new chemicals which may serve as starting materials for explosives or new processes which make for greater production and reduced costs of standard raw materials. In no better way can the effectiveness of this practice be visualized than to observe briefly the development of the three explosives which can be regarded as the minimals of ammunition; namely, TNT, tetryl, and lead azide.

The research organization of the Ordnance Department had followed closely the commercially developed processes for the production of toluene from petroleum hydrocarbons; had checked the quality of the toluene obtainable from pilot operations, and visualized the potentialities of the commercial development during the 10-year period prior to 1940. This one development changed the complexion of the high explosive procurement problem by permitting a much needed increase in the available supply of toluene. This, when coupled with the improvement in the process for the manufacture of TNT and the improvement of the quality of TNT, resulted in high grade TNT at a cost one-third or less than that of the former inferior grade, in quantities to meet all demands.

A new process for the manufacture of high grade tetryl was first studied and evaluated by the research organization of the Ordnance Department during 1923–25. The commercial availability, 15 years later, of an essential raw material permitted this process to be introduced into the manufacture of tetryl in time for this War. This and other developments resulting from chemical research work on the tetryl process also made possible the present production of a chemically pure tetryl having much improved functioning characteristics at a cost approximately one-third that of the inferior material used previously.

Deficiencies existed in each of the high explosives of World War I and much defective ammunition was produced in consequence. As a result of research work over the 20 years between the Wars, these deficiencies were either overcome or new explosives introduced to replace those not subject to correction. The replacement of mercury fulminate by the more stable lead azide is an outstanding example of the elimination of an explosive whose inherent properties prevented substantial improvement.

The record with respect to propellent powders is equally if not more impressive. It is sufficient for present purposes to state as a fact that each and every propellent powder in use by the U. S. Army in this War, comprising about 10 different types, has been adopted since the close of World War I. These new powders have resulted from research work by both Ordnance Department laboratories and laboratories of private concerns experienced in this particular field. Except for rocket propellants, which are almost entirely a development of the last five years, the improved propellants manufactured during this War were conceived, developed, and standardized during the period between 1920 and 1940.

Production of propellent powders had proceeded less than a year after the outbreak of this War when the necessity arose for using wood-pulp nitrocellulose. The transition from cotton linters to wood-pulp nitrocellulose was made without confusion or delay. This was not merely a coincidence, but resulted from successful prior research by Ordnance and Industry.

The situation with respect to propellent

powders at the start of this War was duplicated in the case of miscellaneous explosive compositions used by the Army in pyrotechnics, delay powders, and primer compositions. With the sole exception of black powder, which is still standard for artillery cartridge primers and some other applications, all of the flare, photoflash, and colored signal compositions used in Army pyrotechnics; all artillery fuze delay powders, and all artillery fuze primer compositions, are new and improved in one or more respects. Each composition is the result of research and development work between World Wars I and II.

Much has been written recently in praise of the Ordnance-Industry team in the light of its amazing accomplishments in munitions manufacture during the current war. In the field of explosives and propellent powders that team is an old one, although its existence prior to this war was unknown except to the handful of forward-looking individuals who kept the team going. The powder and explosives programs were the first of all the major programs to get under way and were in full swing when war was declared. These programs were put into operation so quietly and effectively that the country at large either was unaware of the accomplishment or took it for granted. This accomplishment was neither an accident nor a matter-of-fact incident; the story could easily have been a different one and tragically so! Behind these programs lay twenty years of sound planning coupled with the indispensable and very successful research and development achievements of the joint activities of the Ordnance Department and Industry.

It might appear that too much emphasis has been placed on research and development activities prior to 1940, to the exclusion of the War period. Faced with the planning of a research and development structure for the postwar period the immediate inclination is to appraise the accomplishments of the period preceding this War to observe wherein they were adequate in anticipating and preparing for the major demands of the War. It seemed that this would be a natural point of departure for charting the road ahead.

A recounting and evaluation of the output of the numerous agencies and individuals who participated in research and development activities during this War would constitute an historical document of major proportions. It must suffice at the moment to make grateful acknowledgment of their contributions not only to the war effort but to a substantial augmenting of the technical and scientific literature of explosives and propellants that will prove of great value in the research of the future.

Furthermore, the extensive participation in research and development by universities, industries, and groups not heretofore involved or even aware of the problems of explosives and propellants has developed many competent specialized technicians scattered throughout the country. The utilization and perpetuating of this treasure house of scientific talent poses a problem for the post-war planner in order that this talent may be properly fitted into the research and development operations of the Armed Services.

Anyone who has had the responsibility during this War for carrying on research and development very early made the discovery that his two most precious assets are time and talent. An analysis of industrial operations of World War I yielded a list of facilities and materials, the availability of which in the desired quantities would be critical. This list of criticals served as a basis for planning activities during the period between the Wars. Especially critical will be the availability of competent professional manpower which, as applied to explosives and propellants, means chemists, physicists, and chemical engineers. At no time during this war has the supply equalled the demand for this class of personnel in the vital activities with which the writer is familiar. No branch of research and development demands more of its votaries in professional education, specialized training, and experience to fit them for their duties. Assignments can, of course, be found for the competent independent researcher, but the fundamental problems of military explosives and propellants involve multiple fields of scientific endeavor wherein the research team is a prerequisite for timely, productive accomplishments. The ever-present hazard that is a unique characteristic of explosives demands special facilities, instrumentation, and techniques, as well as selected geographical locations.

There is a dawning realization that the lavish expenditures of men and materials by a nation which had never seriously questioned the extent of its resources is a thing of the past. The elimination of waste depends on sound decisions which stem from the availability and use of accurate comprehensive information that, in the nontactical domain of national security, must be the contribution of the research organization.

The planning, directing, and guiding of the research and development activities essential to national security should be the responsibility of organizations which are prepared and empowered to work enduringly, elbow to elbow, with those who set the pattern of the national military policy within the framework of the national economy.

THE RESEARCH AND DEVELOPMENT OF MATERIALS FOR ORDNANCE MATERIEL

By Colonel J. H. Frye
Assistant Chief, Research and Materials Division

THE Ordnance problems of the Assyrian Army in its preparation for invading Babylon and Egypt (about 700 B.C.) were probably comparable to those of modern times, if consideration is given to the differences in scientific and engineering advancement. It was the first Army to be fully equipped with iron weapons. The problem of smelting sufficient iron by their crude furnaces and hand forging it into spear heads and swords must have been tremendous, but the superiority gained by utilizing the "new" material enabled them to defeat their enemies decisively.

With the passage of time and with the attendant progress in the arts and sciences, mankind availed himself of a wealth of new materials, new processes, and new fabricating procedures. These came to be regarded as the intangibles of war and in days past as at present, the Army which utilized them to the maximum had the advantage.

In present day production of nearly 2000 standard Ordnance items there are consumed almost unbelievable quantities of all types of materials. Each of these items has definite requirements with respect to such military characteristics as safety, firepower, weight restrictions, longevity, interchangeability, transportation, and quantity production. The type and quality of the materials entering into the construction must be such as to produce the required military characteristics in the end product. It is paradoxical that the production of materials for war is expanded in times of emergencies and at the same time the over-all quality level must be raised. Service failures in commercial products result in the loss of sales or dollars, whereas service failures of war materiel cost human lives and perhaps battles.

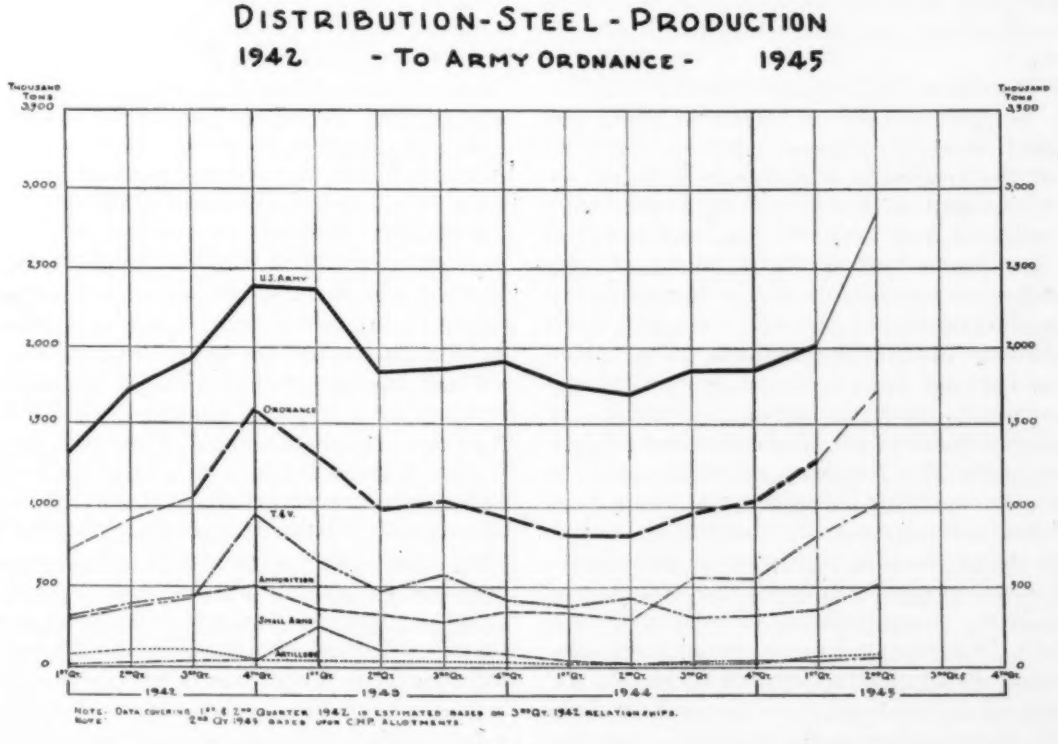

FIG. 1.

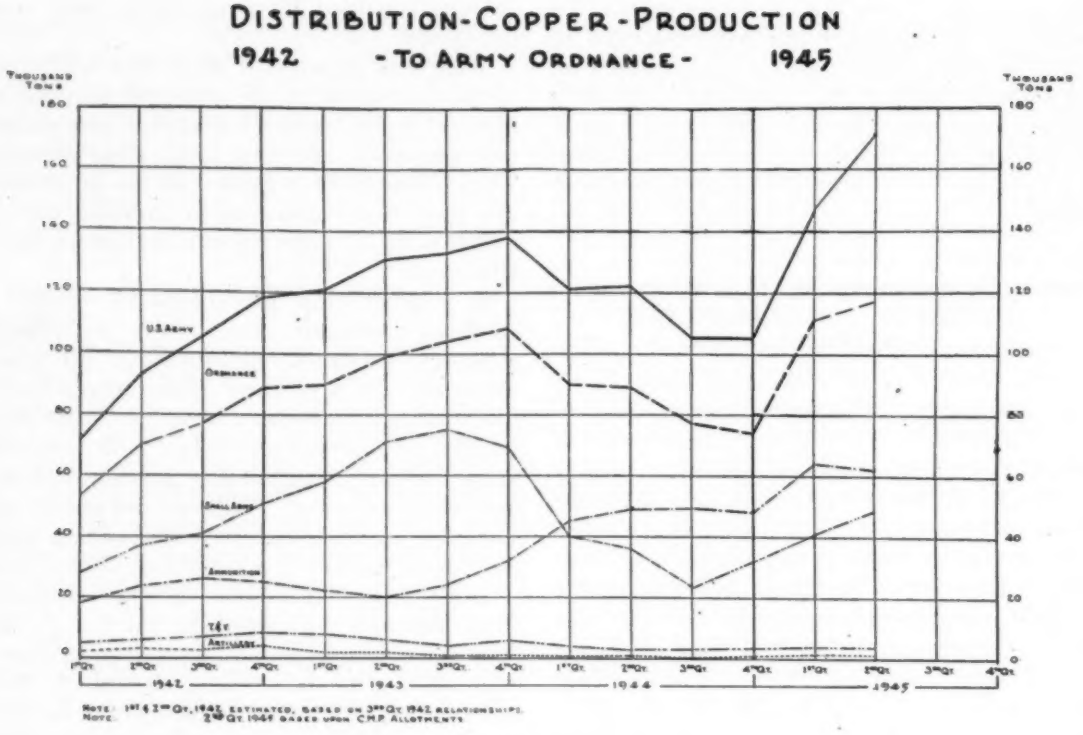

FIG. 2.

This places an abnormal burden upon the scientific, engineering, and production facilities of a country.

The Ordnance Department depends upon industry to produce the materials required for structural or constructional purposes, and, in view of the tremendous quantities required in times of national emergencies, it is essential that their selection and usage be confined to those types and grades that can be obtained in mass production. As an example, Fig. 1 illustrates the consumption of steel by the Army, the Ordnance Department, and its four manufacturing Divisions for the past three years, while Fig. 2 shows the data on copper consumption. The values for the last two quarters are allocations and subject to corrections. The relative availability of rarer metals and materials is equally as acute even though their measure may be in ounces or carats.

Since the production of new or improved materials offers an opportunity further to improve the military characteristics of materiel, the Ordnance Department fosters research and development of this nature. Some of this work, for very special applications, is performed by such scientific organizations as the National Academy of Sciences and the National Research Council. Some is done by Ordnance Arsenals or by direct contract, but by far the greatest share is performed by industry and technical societies. After a new or improved material is developed, it must ordinarily be available in relatively large commercial quantities; hence the need for securing the cooperation and collaboration of industry is obvious. The beneficial results of the full cooperation of science and industry is of equal importance in peace years. The designs made during that time are the basis of protection in emergencies and the materials selected must be used in the initial mass production of materiel.

Those materials of critical or strategic importance receive special attention. The Ordnance Department recognized the strategic importance of cutting tool steels and in the early 1920's Watertown Arsenal, in cooperation with industry, did some of the basic research that resulted in the substitution of molybdenum for tungsten in those steels. One interesting and possibly important research program concerning steels treated with hardness intensifying agents is now underway. By this means it may be possible in the future to reduce the difficulties and handicaps of ferro-alloy shortages which beset us during this war. There are materials used in Ordnance

items for which there are no commercial peacetime counterparts. Such items as armor plate and castings, gun tubes, high explosive shells, and armor piercing shot, and similar items require steels of special composition and characteristics. Cartridge brass, explosives, incendiary compositions and other materials of purely military applications require continuous research and development work by Ordnance agencies.

There are many materials of a commercial nature which must be modified to a more or less degree to make them suitable for war materiel. As an example, the humid climate of the tropics causes rapid deterioration and early in the war it became evident that adequate provisions to protect against destructive moisture and fungus attack would have to be made. Attention was initially concentrated on the four types of equipment most urgently in need of protection—cotton fabrics, leather items, optical instruments, and electrical equipment. Without this protection there would be excessive replacements, utilization of critical shipping space, personal discomforts, loss of morale, and even the malfunctioning of equipment which could affect the pursuit of the war in a direct and positive manner. For instance, antiaircraft guns are automatically controlled by fire control instruments through electrical devices, and tank and motor vehicle functioning is dependent upon electrical and fire control systems.

The services of the Department of Agriculture, National Research Council, Society of Automotive Engineers, fungicide manufacturers, and of industry engaged in the production of these items and materials were secured. The protection of fabrics and leather was complicated by the restrictions against the use of fungicides toxic to the human body. The work is essentially completed and tentative protection measures have long since become a part of specifications for critical items.

The moisture and fungi reactions on optical instruments not only obscured vision by etching the glass, but also corroded the metals parts and decomposed the cement, allowing separation of the component parts. A volatile fungicide and the technique of incorporating it into the instruments were developed and are now in use. The carrying cases for optical instruments are a composite of leather, cardboard, felt, and cloth, all susceptible to mold growth which in turn serves as a source of primary infection to the instruments. A treatment to resist mold growth and at the same time provide water proofing to these cases and other leather parts was developed and is being used. The protection of electrical equipment is more complex. At the present time, degradation by fungi and moisture is retarded by the elimination of cellulosic material susceptible to fungi attack, and by the use of sealing and protective coatings to reduce contact moisture effect. One difficulty which has not been entirely corrected is caused by the "breathing" of sealed inclosures, and more work needs to be done in this direction.

The development and improvement in materials, particularly during the past few years, have been remarkable. Not only have the qualities and usefulness of common types been greatly expanded, but through scientific research new types have been introduced.

The loss of crude rubber was staggering to the Ordnance Department since the Army literally rides into battle on rubber. Concurrently with the amazing development and improvement of processes for making synthetic rubber and the building of plants, the Ordnance Department intensified its programs for converting all natural rubber components to synthetic types as rapidly as possible. The introduction of new and improved plastics as an engineering material and their use for making stressed functioning parts was an important contribution. While magnesium cannot be construed as a new material as it was used commercially to a limited extent for structural applications before the war, it is essentially a new Ordnance materiel. Until recently, it was not available in sufficient quantities to be considered, except for signals and flares. Sizable quantities are now used to lessen the weight and gain mobility of materiel, with promising possibilities of increased usefulness. In the field of light metals the number of aluminum alloys useful to Ordnance construction has increased from five to twenty in recent years. Steel is basically a common material, but the performance of the industry in developing qualities of new and different characteristics for specific applications is outstanding.

It is impracticable to mention even the most outstanding advancements in materials of importance to Ordnance. The number is great and their contribution to the conduct of war is beyond reckoning.

New and improved materials for the construction of Ordnance materiel are expressed and reflected in the terms of specifications. The preparation of specifications is an important phase of

the selection and application of materials. In addition to serving as procurement documents, they have several secondary functions, including the cataloging and classifying of materials for design engineers.

Insofar as practicable, Ordnance material specifications conform to commercial standards. They are prepared with the assistance and cooperation of industry and in each case they are referred for comment and criticism to representative producers and industrial organizations before issuance. The value of such a procedure is threefold; first, to retain industrial standards of quality and inspection insofar as practicable and thus insure immediate availability in periods of national emergencies; secondly, to supplement the technical knowledge and experience of Ordnance engineers in meeting quality requirements in the most expeditious manner and at lowest cost in man-hours and money. Thirdly, it is important that industry be familiar with the quality requirements and peculiarities of materials for Ordnance, and this close cooperation and coordination effect that end.

In addition to membership or close liaison with scientific groups and organizations, the Ordnance Department has maintained membership or observers in engineering and technical societies, such as American Society for Testing Materials, Society of Automotive Engineers, American Standards Association, and others. The many trade associations of industry, such as the American Iron and Steel Institute, American Die Casting Institute, etc., have been of real and material assistance in preparing and maintaining Ordnance Department specifications. There can be no question that without the help of the scientific and technical people of the nation, it would have been impossible to swing from the limited peace time procurement of 1938 to the mass production of materiel in 1940 without confusion and costly delays. The rapid pace of scientific and technical development requires a continuation of this work to a degree commensurate with the rate of advancement.

The selection of the methods of processing and fabricating of component parts is of equal importance with the selection of materials. Frequently one is dependent upon the other, and occasionally the two are so closely associated that they cannot be separated. The need for the mass reproduction of parts utilizing minimum man hours, vital machine tools and materials is self-evident. In periods of emergencies the Ordnance Department must fully utilize the knowledge, skill, and manufacturing facilities of the nation. Advantage must be made of commercial fabricating and processing facilities, not only because they are immediately available but also to produce war materiel in the enormous quantities required. Ordnance engineers must design materiel that is amenable to the limited peace-time production, yet be capable of mass production without notice. This necessitates a full and continuous partnership with science and industry.

As with materials, the advancement of processing methods is naturally and logically carried forward by industry and it is essential that Ordnance engineers maintain close coordination with the various branches of industry to keep abreast of their developments. There are exceptions where there are no commercial counterparts of certain military items and in such instances Ordnance, through its arsenals or by contracts, conducts the research and development work. One outstanding example of the latter is the centrifugal casting of light and medium caliber gun tubes, which was developed at Watertown Arsenal prior to the war. The pioneering and subsequent development of this means of rapid production was an extremely important factor in supplying our armies with sufficient and superior firepower. The earlier work which resulted in cold working of gun tubes provided greater strength, permitting higher muzzle velocities and lighter weight guns. Continuous research is conducted on the processing and fabricating of armor, armor piercing shot, cartridge cases, and other items pertaining primarily to military end products.

Full utilization has been made of industrial progress in the heat treatment of metals. At the Shiloh winter proving ground, Ordnance engineers conclusively determined that armor plate or castings must be fully quenched out and tempered to secure the desired ballistic properties. Before the war, the production of armor piercing shot was a restricted art and high alloy steels and trick heat treatments were considered essential. Through the coordination and cooperation of industry and Ordnance the alloy content has been reduced to the level of a common type of alloy steel, production methods have been evolved, and improvement in ballistic characteristics has been effected by improved heat treatments. There is some interesting development work under way at the present time relative to the use of martempering medium caliber A.P.

shot. Preliminary results indicate superior ballistics with relative freedom from incipient cracks and distortion.

Methods of heat treatment, such as cycle annealing, flame hardening, and induction hardening, have been adopted and have played a major role in the quantity production of units and components having the necessary and dependable properties.

Both the usual and unusual methods of producing components and assemblies have been exploited and used where such applications would improve the quality of the end product, result in increased production, or savings in man hours or materials. The need for developing and improving such methods is self-evident, but a classic example of their value to the production of war materiel is that of fuze components. Prior to the "Emergency," the limited procurement of fuzes, and the more limited budget, required these components to be produced on automatic screw machines from aluminum bar stock. Not only was it impossible to meet the war requirements by machining, but the expanding aircraft industry had priority on the wrought aluminum. A grade of aluminum too impure for wrought products, but satisfactory for die castings, was developed with the assistance of the War Production Board, American Die Casting Institute, and the die casting industry. The latter then developed casting techniques and quality control methods that enabled them to produce die castings of a quality and uniformity previously unknown.

Welding has played a vital role in the fabrication of materiel. The change-over from riveted to welded tank construction is well known, as is its importance in reducing the weight of artillery and making possible the DUKW. There has been tremendous advancement in the art and technique of welding. With the National Defense Research Committee and the American Welding Society and Industry, the Ordnance Department has actively participated in this development. A new type of ferritic electrode for welding steel of high hardenability has been under development and there is every indication that fabrication by welding will be given new impetus.

The use of steel stampings to replace castings, forgings, and machined parts has been developed extensively. Components made by powder metallurgy, investment castings, extrusions, and various other methods of rapid reproduction have made it possible to arm this and allied nations in time to defeat the enemy.

The continuous development and improvement of materials and processes have created a complex structure with which the designing engineers must cope. Fifty years ago, the materials and fabricating processes were within handbook coverage, and designers could properly place specifications on drawings. The selection of materials, processing, and method of fabrication has broadened greatly. In addition, the Ordnance Department must constantly bear in mind the potential shortages of critical or strategic materials in periods of peak production, the adaptation of processing and fabricating methods to existing equipment and industry standards, and other factors that will permit either limited peace time or peak war production. It is essential that qualified materials engineers be available to assist designers at the drafting room stage. To reduce the danger of shortages, it is considered essential that two or more materials and two or more methods of processing be specified for each component.

To be prepared to meet emergencies which may be caused by war minded nations in the future, it is necessary for the Ordnance Department to be allocated sufficient funds to provide adequate technical and scientific personnel and to design for limited and mass procurement.

FUELS AND LUBRICANTS

By Lt. Colonel R. E. Jeffrey, Jr.

PETROLEUM products presented no particular problem for the Army in World War I, but the Ordnance Department, in planning for our World War II mechanized Army, early realized the importance of fuels and lubricants to the successful performance and maintenance of materiel of all types. A research and development program was started to provide fuels and lubricants specifically designed for their military application.

Responsibility for the Ordnance research and development program for fuels, engine oils, preservative lubricants, rust preventive compounds, greases and recoil and hydraulic oils, has rested with the Fuels and Lubricants Branch, Research and Materials Division, Research and Development Service. In addition to these activities, the Fuels and Lubricants Branch is responsible for the investigation of enemy fuels and lubricants. Personnel in the Branch have been carefully selected for their previous in-

dustrial experience in the field of fuels and lubricants research and development.

The Fuels and Lubricants Branch has been ably assisted in its work by the Coordinating Research Council, an industry group jointly sustained by the American Petroleum Institute and the Society of Automotive Engineers. By utilizing the technical skill and experience of the petroleum and automotive industries through the Coordinating Research Council, the Fuels and Lubricants Branch has been able to accomplish a great volume of work in a relatively short period of time. The activities of the Fuels and Lubricants Branch have not been confined to Ordnance problems alone, but include fuels and lubricants development problems for the entire Army Service Forces, as well as cooperative work with the Navy Department and the Army Air Forces. In many instances difficulties were anticipated and provided for before they could hamper military operations in the combat theaters.

During World War II our forces have carried out offensive operations simultaneously in almost every part of the world. Satisfactory performance of equipment has been required under almost every conceivable condition of temperature and terrain. In developing petroleum products to meet those conditions we have had to go far beyond the limits established by previous commercial experience. The development of a single combat gasoline in which both equipment and supply considerations had to be weighed clearly illustrates the point.

Based on the requirements of individual engines, three types of gasoline for combat and motor transport vehicles were necessary in 1940. As a result of extensive tests, which included modification of one tank engine, it was determined that an 80 octane number fuel would serve as a standard combat fuel for all Army vehicles. At that time commercial premium grade gasolines of the quality required for military use were available in sufficient quantity to meet Army requirements. A specification was written to permit procurement of the premium grade fuel.

However, the 80 octane number premium gasoline was supplied in three volatility grades in accordance with commercial practice of supplying fuels adapted to the season and the area in which they were to be used. This method of supply required definite knowledge of the area to be supplied and the season of the year when the fuel was to be used. So long as the bulk of our forces were in training in this country no difficulties were encountered in supplying the correct grade of fuel. However, it was anticipated that insurmountable supply problems would arise as soon as our forces moved to bases overseas and began to build up large stock piles for future operation. It was apparent that a single 80 octane number combat gasoline was desirable, and that it must cover as wide a temperature range as possible.

The development of a single combat gasoline required the investigation of two important factors; vapor lock and cold starting. From commercial experience it was known that gasolines differ greatly in their tendency to form vapor and that vehicle fuel systems differ in their tendencies to vaporize fuel as well as their ability to handle vapor. Therefore, tests were conducted at El Centro, California, under extremely high temperature conditions to investigate vapor lock from the fuel standpoint and vehicle fuel systems from the standpoint of their gasoline handling characteristics. Those tests which were made in the summer of 1942 determined the proposed specification limits which would afford the maximum vapor lock protection without sacrificing other desirable characteristics of the fuel, and at the same time indicated certain changes to be made in vehicle fuel systems.

In the fall of 1942 the first American armored units which entered the United Kingdom experienced cold starting and warm-up difficulties at temperatures slightly above freezing, with 80 octane number gasolines meeting the maximum volatility limits of the specification. Tests were run in this country with a group of tanks using a number of gasolines of different volatility characteristics. Based on data from those tests and the information from the United Kingdom, a test fuel was formulated and furnished to the Ordnance Winter Detachment then in camp in Manitoba, Canada. Here records were obtained of the starting and warm-up characteristics of various combat and transport vehicles under the existing low temperatures.

Data obtained at both high and low temperatures were studied in the light of available materials by representatives of industry through the Coordinating Research Council.

As a result of those cooperative studies it was concluded that a single grade of fuel, providing satisfactory operation over the temperature range of 0°F to extreme heat, could be obtained in the quantity required without disrupting refinery operations or infringing upon the requirements of the aviation gasoline and rubber programs. It

was known that the greatest requirements for combat gasolines would come from areas within the 0°F to extreme heat temperature range; therefore, this single grade would represent most of the gasoline used. A second grade of gasoline, which is needed only in very small quantities, was provided for below 0°F operations. U. S. Army Specification 2-103B was written covering those two grades of gasoline, and after correlation with industry and the appropriate military and governmental agencies, was issued in November, 1943.

The development of the single combat gasoline followed a pattern which has been consistent throughout the activities of the Fuels and Lubricants Branch. Early in the war commercial products were adapted to military use wherever possible. As the quantity of military equipment was steadily increased, more was learned about the fuels and lubricants requirements of the equipment. In many instances service tests indicated modification of commercial fuels and lubricants to fit those materials to military use. At the same time the increased demands for petroleum products necessitated the use of base stocks of poorer quality. This made it difficult to formulate finished materials having the characteristics required for military use. The goal has always been simplification of overseas supply to the fewest number of fuels and lubricants necessary for satisfactory operation and maintenance of Ordnance materiel. Throughout the pattern of development, availability of materials and ease of manufacture have been considered and coordination with industry and other agencies has been practiced. By this means commercial products have been developed into strictly military materials without undue hardship to the refiner or to the civilian economy.

The development of the present engine oil followed the usual pattern. Early simplification was possible by the elimination of unnecessary viscosity grades and the development of a specification to provide for procurement of acceptable commercial products. Two types of engine oils were used: a straight mineral oil in three viscosity grades for gasoline engines and heavy duty type oil in two viscosity grades for diesel engines. The straight mineral oils provided no problem, being adequately covered by U. S. Navy Specifications. However, the preparation of a specification for heavy duty engine oils presented many difficulties because oils of that type require extensive engine testing before they can be safely evaluated. In commercial practice the Caterpillar Tractor Company and the General Motors Corporation made extensive engine tests before approving heavy duty oils for use in their diesel engines. Neither the Caterpillar or the General Motors tests completely evaluated oil performance, but a combination of both would. After careful consideration and coordination with engine manufacturers and oil refiners, a specification was prepared requiring U. S. Army heavy duty engine oils to pass both these engine tests.

As the military operation of motor vehicles increased both in extent and severity, corrosion of alloy bearings was experienced with the straight mineral oils. Since it was apparent that the heavy duty engine oils were the most suitable for all engines under all operating conditions, another viscosity grade was added to the specification and the heavy duty type oils were prescribed for use in all U. S. Army vehicles. This action reduced to three the number of grades of engine oil required for all vehicles and at the same time improved maintenance by controlling alloy bearing corrosion and eliminating ring sticking, valve sticking, and high oil consumption.

Continued operating experience indicated several other requirements not adequately covered by the specification. When engine oils are agitated in the presence of air, foaming occurs. With straight mineral oils the foam breaks quickly, but some additives used in heavy duty oils apparently stabilize foam. The problem then becomes quite serious, particularly in the dry pump engines used in tanks. Extensive service tests were made with foam-inhibited heavy duty oils to determine the effectiveness of the inhibitors. A laboratory test method was developed which closely correlates with the service tests and has been included in the specification.

Some engine oils after exposure to sub-zero fluctuating temperature cycles show a higher pour point than was originally indicated by laboratory determination. This phenomenon, commonly referred to as pour-point reversion, was noted both in Alaska and Canada during sub-zero service tests. It was found that pour-point reversion could be held to a minimum by careful selection of base stocks and use of the correct amount of pour-point depressants. The problem was to develop a laboratory pour-point test which would properly evaluate this characteristic. Through the assistance of the Coordinating Research Council a laboratory method

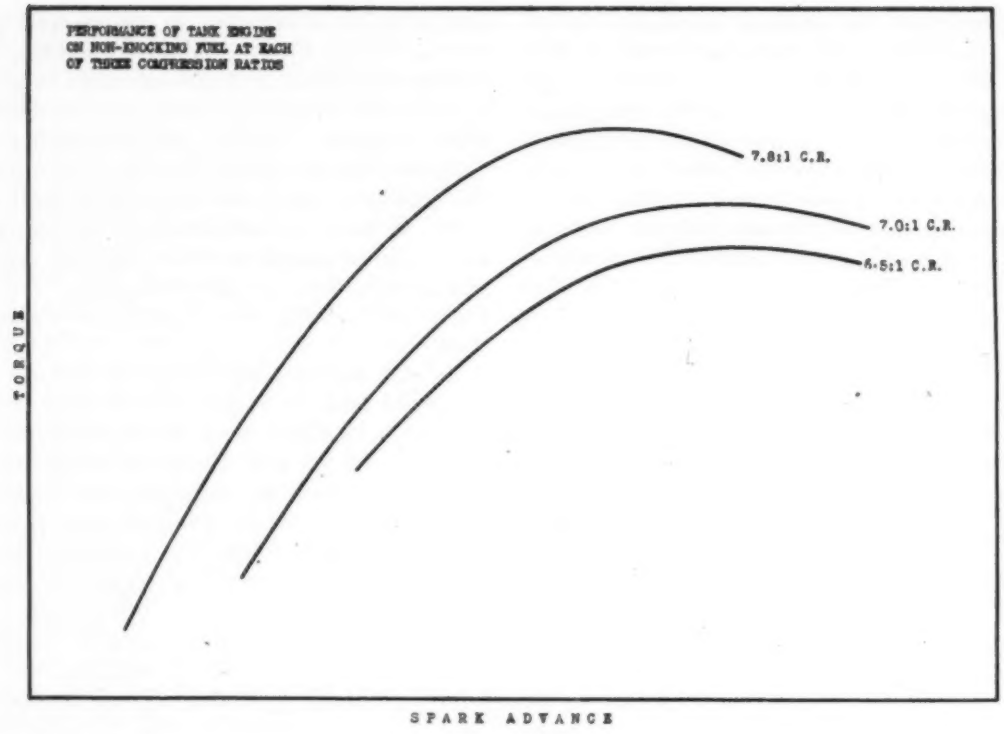

FIG. 1.

was developed and has been included in the specification.

The satisfactory performance of artillery materiel, particularly at the temperature extremes, depends greatly upon the oil used in the recoil mechanisms. Early preliminary simplification reduced the number of recoil oils in use from seven to two seasonal grades. Unsatisfactory performance at the borderline temperatures, the time required and the difficulties involved in changing recoil oil in the field clearly indicated the need for a single all-temperature recoil oil. Much of the research involved was of a pathfinding nature. To cover the wide temperature range the oil required a viscosity index higher than that of any oil commercially available. Since the oil was to be used in existing mechanisms, its density, stability, and effect on packings were important factors to be considered. In collaboration with NDRC an oil was developed which proved satisfactory after tests in which 133,000 rounds of ammunition were fired at temperatures from −45°F to +140°F. That oil is now the standard recoil oil in use by the U. S. Army.

The swift extension of military operations to all parts of the globe created entirely new and extremely difficult problems of rust prevention and surface preservation. The high humidity of tropical areas and salt air contribute to rapid corrosion. Rust preventives for protection of all types of materiel during use must lubricate the materiel as well as protect it from rust. Among the products developed are preservative oils for aircraft armament, small arms and artillery, and for the interior of engines. Each has been designed for a specific purpose. The preservative oils for aircraft armament not only furnish adequate protection from rust but also permit satisfactory performance of weapons at temperatures as low as −70°F. Small arms and artillery preservative oils permit satisfactory performance of those weapons at all temperatures encountered by the ground forces and keep the weapons ready for immediate use with a minimum of attention to prevent corrosion. Engine preservative oils protect the engines against rust in shipment and storage and also serve as the crankcase lubricant for limited periods of time. Vehicles prepared for shipment with preservative engine oil can be put into service immediately upon arrival at their destination and can be continued in operation until arrival at a point where crankcases can be drained and refilled with standard crankcase lubricant. By this means the maintenance prob-

lem of reconditioning rusty engines or removing preservative materials before putting the engine in operation has been eliminated.

The development activities of the Fuels and Lubricants Branch did not end when a product was developed and a specification was established. A continuing program of development has been necessary to maintain the quality level of the finished products. For example: the oxidation stability of 80 octane number gasoline was excellent during the early months of the war, but increased demands necessitated the use of much less stable stocks as the war progressed. A serious gum problem was anticipated in the theaters where large stock piles must be accumulated for future operations. There was practically no commercial experience available to serve as a guide for the use of deteriorated stocks, or as a test to determine a stable gasoline.

The urgency of the situation demanded immediate action; therefore interim action was taken to include a stability requirement in the specification. To confirm this action and to define more exactly the stability requirements, a storage stability test was made under elevated temperatures at El Centro, California. Other tests were run in hot rooms to correlate laboratory results with the actual storage conditions. Those tests produced pertinent data, which in general substantiated the interim action taken.

A similar situation arose with respect to heavy duty engine oils. When a scarcity of the additive materials used in those oils appeared imminent, severe service tests were conducted to determine the minimum additive content required. As a result of those tests, substantial savings were made in the quantity of additives used without detracting from the desirable characteristics of the oil.

The activities of the Fuels and Lubricants Branch have not been confined solely to the development of new or improved products for Army use. A detailed investigation has been made of enemy fuels and lubricants. Selected industrial laboratories, assisting the Ordnance Department, through the Coordinating Research Council, have made research analyses of all such materials received in this country. The source of the crude oil, methods of refining, and synthetic or substitute materials used have been determined. Based on these data, information concerning the adaptability of enemy petroleum supplies to use in our own equipment has been quickly forwarded to the theaters, since it is sometimes necessary to

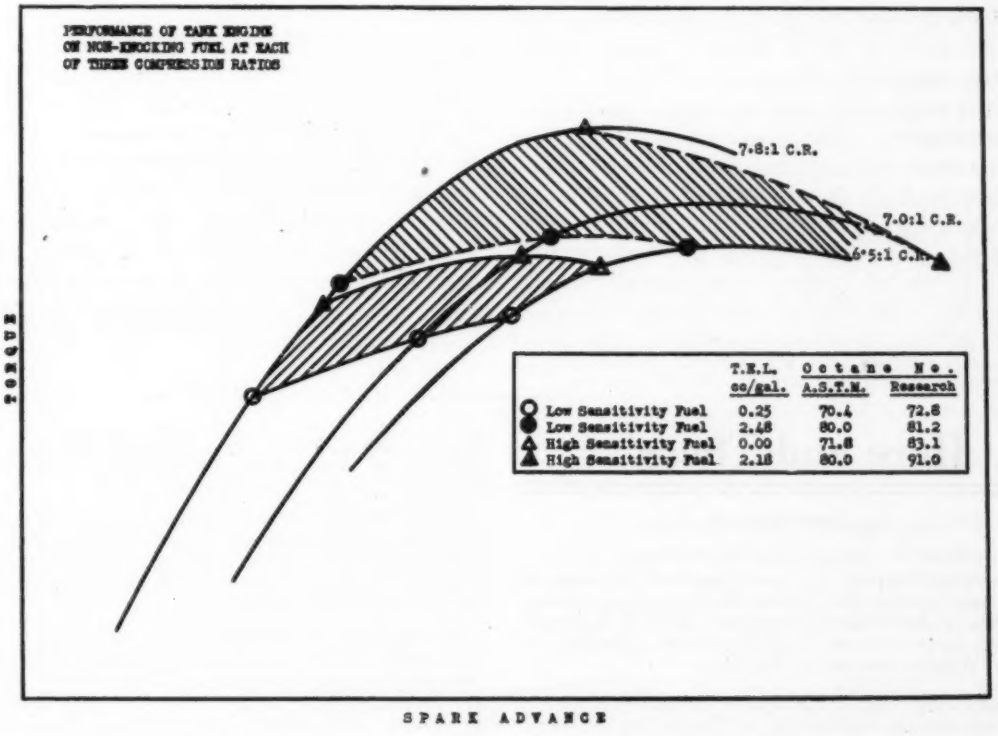

FIG. 2.

sustain a rapid advance through the use of enemy materials when operating at the end of extended supply lines. Data concerning the source of the enemy materials and the methods of refining are forwarded to other agencies responsible for assigning air target priorities and evaluating the enemy's oil position. The Fuels and Lubricants Branch is doing this phase of the work not only for the Ordnance Department but for the Navy Department, Army Air Forces, and various governmental agencies.

Experience gained during the war clearly demonstrates the need for continued Ordnance research and development work on fuels and lubricants. Although much has been accomplished, current trends indicate that materials now in use will be outmoded shortly after the end of this war. New equipment design will influence the characteristics of fuels and lubricants; therefore it is essential that the development of those materials proceed concurrently with that of new materiel. This can be illustrated by the work to determine engine fuel relationship, which has been in progress for some time, and should be a continuing activity.

It has been generally known that one way to increase the power output of an engine is to increase the compression ratio. However, this is only true if the fuel used is one that will prevent engine knock under all operating conditions. The following analysis of a modern tank engine illustrates this point.

Figure 1 shows engine performance curves (for the same engine) with change in spark advance for three compression ratios when operating on a non-knocking fuel. It will be noted that under those operating conditions the highest compression ratio gives the highest power output.

Figure 2 shows engine performance curves (again for the same engine) with changes in spark advance for the same compression ratios when operating on four commercial fuels: two of 70 octane number and two of 80 octane number. The two 70 and the two 80 octane number fuels differ from one another only in sensitivity to knock. Those differences exist because of different crude sources and methods of manufacturing the gasoline. It will be noted that 70 octane number gasoline with high sensitivity operated on a 7 to 1 compression ratio will give more power than an 80 octane number gasoline with low sensitivity operated on a 7.8 to 1 compression ratio. Engines vary in their knocking tendencies, and this comparison does not necessarily hold for all engines. It is essential that engine fuel relationship be considered in any change in fuel or engine design and in this respect the project may be considered a continuing one.

Military characteristics of tanks show a trend toward even greater compactness than is now the case. It is entirely possible that in the near future, tank engines will be expected to operate without oil coolers. The development of engine oils which will insure satisfactory operation at the resulting high crankcase temperatures is anticipated.

The subject of rust prevention offers a fertile field for future research. The Ordnance Department, which is responsible for the preservation of great quantities of equipment for many years, needs rust preventives which will give long-time protection without interfering with the operation of the equipment. Quick, yet positive, methods of evaluating such products are also needed.

The Ordnance Department plans to continue its research and development activities on fuels and lubricants. Many problems, unforeseen at present, are expected to arise with the development of new equipment of all kinds. The successful solution of those problems will depend to a large extent on the continued cooperation of industry and Ordnance.

Here and There

New Appointments

Science reports the following personnel items:

Dr. Vladimir Rojansky has been appointed chairman of the department of physics of Union College to succeed the late Dr. Peter I. Wold. Since November, 1943 Dr. Rojansky has been on leave of absence as a consultant on special war projects in Washington and in England.

Professor Ernest Horace Lamb, for 32 years professor of civil and mechanical engineering at Queen Mary College, London, will retire at the end of the present session. He will be succeeded by Dr. Edmund Giffen, since 1940 director of research at the Institution of Automobile Engineers' Laboratories at Brentford.

Leonard O. Olsen and Eugene C. Crittenden, Jr., assistant professors of physics at Case School of Applied Science, Cleveland, Ohio, have been promoted to the rank of associate professor. Professor Crittenden has been on leave of absence for war service.

The Midwest Research Institute, Kansas City, Missouri, has added nine new members to its staff, bringing the total personnel of the Institute to 71: Dr. Frederic W. Jung, Dr. Robert R. Hancox, Dr. Robert W. Shortridge, Lorenzo D. Moore, John Affleck, Jerome Brewer, Carl R. Johnson, George W. Swehla, and Louise T. Alderman.

Ohio State Receives $100,000 for Use in Fundamental Research

A contribution of $100,000 to be used in the encouragement of fundamental research has been received by Ohio State University from its Research Foundation. This sum, according to Dr. A. R. Olpin, secretary and executive director of the Foundation, represents a return to the university for the use of its facilities in governmental and industrial research. It is taken from the Foundation's research reserve, accumulated through earnings from patent licensing and other sources.

It is expected that all or most of the $100,000 will be used in the creation of fellowships at Ohio State. The fund will be allocated under the direction of President Bevis, with the concurrence of Dr. Olpin. To assist in the drafting of policies and procedures, Dr. Bevis will appoint a committee including representatives of the president's office, the Foundation, the Graduate School, engineering, the physical sciences, the biological sciences, and the social sciences.

During the past three years Ohio State's nine-year-old Research Foundation has administered an average of two million dollars in contracts annually, some for industry, others for government. Two major war-time activities were the Recognition School, in which nearly four thousand men were given training for the U. S. Navy in methods developed at Ohio State, and a project relating to the atomic bomb production. New projects are constantly being added, fourteen additional contracts amounting to $256,580 having been approved in one month recently.

Baker Instrument Company

Frank C. Baker, Jr., formerly service and sales manager of the Scientific Glass Apparatus Company, has recently formed the Baker Instrument Company, located at 310 Main Street, Orange, New Jersey. This new organization will be devoted to the sale and service of technical equipment for laboratory and pilot plant.

Conference on Instrumentation

A conference on "Instrumentation and the University" was sponsored by the Carnegie Institute of Technology and The Instrument Society of America at the Carnegie Institute of Technology, October 16 to 18, 1945. Its purpose was to provide an opportunity for an exchange of views among industrial instrument users, government agencies, instrument manufacturers, and the faculties in engineering and science. Speakers presented papers covering the following questions: How has the educational work been carried out heretofore in either schools or industry? What undergraduate instructions would be desirable? How can postgraduate work contribute to the training? What can the university best contribute to the field of research in instrumentation?

Gas Turbine Laboratory at MIT

The Massachusetts Institute of Technology has received gifts totaling half a million dollars for establishing a gas turbine laboratory for graduate instruction and fundamental research. The laboratory, which is to be completed as soon as possible, will undertake a program of specialized technical studies aimed at the discovery of new techniques required in the construction of machines operating at extremely high speed, high temperature, and high compression. Equipment will include a supersonic wind tunnel and unique facilities for research on the elements of compressors, combustion devices, jets, and gas turbines.

Research Corporation Offers $2,500,000 for Post-War Collegiate Research

Scientists who made the atomic bomb, radar, and a host of other vital war weapons will have a chance to return promptly to college laboratories for scientific research and teaching through $2,500,000 in grants offered to educational institutions by Research Corporation, of New York, a non-profit organization devoted to advancing research and technology by use of revenues from inventions assigned to it by public-spirited inventors. Preference in making these grants will be given, other factors being equal, to smaller institutions and those of more limited financial resources for research.

The five-year program announced by Dr. Joseph W. Barker, acting president, will result in 100 to 200 grants of $2500 to $5000 each year in order that talented young scientists, engaged for the most part in war research in uniform or as civilians, will be able to undertake at universities and colleges research of peace-time importance in pure science, especially chemistry, physics, mathematics, and engineering. The first grants will be made in a few weeks by a special committee of eminent scientists from industrial and university laboratories. The committee is composed of Acting President Barker, who is also Dean of Engineering at Columbia University; Dr. Thomas H. Chilton, director of engineering for duPont; Dr. William D. Coolidge, x-ray consultant for General Electric Company; Timothy E. Shea, manufacturing engineer of Western Electric Company; Dr. Lloyd P. Smith, associate research director of Radio Corporation of America; Col. Stafford L. Warren, Professor of Medicine at the University of Rochester; and Dr. Robert R. Williams, inventor of the synthesis of vitamin B_1 and coordinator of research of Research Corporation.

Grants will be made to the institutions at which the scientists will work and teach. The funds allotted will be available for the purchase of needed equipment and for employment of assistants either as Fellows or otherwise. Awards will be based primarily upon the demonstrated ability of the men who will conduct the researches and contribute to the teaching program of the school.

Bulletin of Mathematical Biophysics

Following is the table of contents for the December, 1945 issue of the *Bulletin of Mathematical Biophysics:*

Chain Processes and Their Biophysical Applications: Part I. General Theory—I. OPATOWSKI.
The Flow of a Viscous Fluid in an Elastic Tube: A Model of the Femoral Artery—HERMAN BRANSON.
A Contribution to the Mathematical Biophysics of Cell Growth and Shapes: I.—RICHARD RUNGE.
Some Remarks on the Boolean Algebra of Nervous Nets in Mathematical Biophysics—N. RASHEVSKY.
Some Quantitative Aspects of Shock Therapy in Psychoses—LEWIS DANZIGER AND H. D. LANDAHL.
A Note on the Mathematical Biophysics of Central Excitation and Inhibition—H. D. LANDAHL.
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The University of Chicago Press, Chicago, Illinois. Vol. 7, No. 4:

National Patent Council Organized

A nation-wide group of smaller manufacturers, representing 28 classes of industries, has been organized as the National Patent Council, with headquarters at Gary, Indiana. It plans a counter-offensive against widely publicized attacks on the U. S. patent system.

Contributed Original Research

Determination of Coexisting Phases in Heterogeneous Systems of Many Components

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(Received February 2, 1945)

A general investigation was made of the coexistence relationships of $n+1$ phases in the isothermic-isobaric sections of n-component systems. It was found that for a given set of $n+1$ phases there are at most only two coexistence patterns possible. As a result in n-component systems, as well as in ternary systems, theoretically only a single well-chosen sample has to be examined for the phases it contains in order to completely clarify the phase coexistence relationships of $n+1$ phases whose composition is already known. The results obtained were further used to develop a general classification of the types of non-variant equilibria occurring in many component systems.

INTRODUCTION

THE study of heterogeneous equilibria found its most important application in the field of metallurgy. However, a serious limitation arose from the fact that alloys of practical usefulness frequently consist of many components, while the study of equilibria in systems of more than three components was often considered forbiddingly complex. It will be attempted in the following to show that at least some of the expected complexity in many component systems can be reduced to fundamentally simple relations.

In almost all metallurgical applications of heterogeneous equilibria it is permissible to neglect pressure as a variable when only liquid and solid phases are under consideration. In such "condensed systems" isobaric equilibria are of the highest practical importance.[1] According to the phase rule for isobaric equilibria the maximum number of coexisting phases is equal to the number of components of the system, with the exception of non-variant equilibria occurring only at certain singular temperatures. Therefore, if in a given system more phases are known to exist at a certain temperature than the number of components, then, in general, they can not all coexist. In such cases, if the identity of all phases is already known, the next problem in determining heterogeneous equilibria at the temperature in question consists in ascertaining which phases may coexist with each other and which may not.

In a two-component system, coexistence of the various phases formed at a certain temperature is uniquely determined by their composition. Therefore, if the identity (composition) of all phases existing at a certain temperature is known, it is immediately obvious which ones may and which ones may not coexist under equilibrium conditions. The rule is very simple. The binary phases can be arranged in a linear order with one component increasing, the other decreasing. At any temperature only neighbors in this series may coexist.

In ternary systems conditions are not so simple. The phases existing at a certain temperature can be arranged according to their

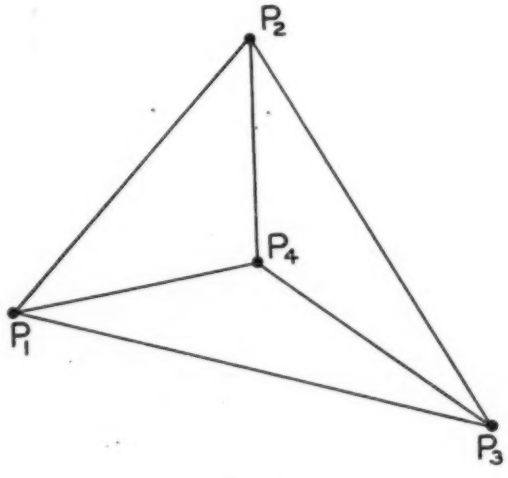

FIG. 1.

[1] In the following only isobaric equilibria are considered. This should be understood, although for brevity's sake no further mention of it will be made.

composition in a two-dimensional order. The geometry of this arrangement is usually given in the familiar triangular diagrams representing isothermic sections of the ternary equilibrium diagram. Of course, if there are only three phases in an isothermic section, no problem arises; all phases may coexist. However, if four phases are formed in the system at the temperature in question, the geometry of their relative positions does not always uniquely determine their coexistence. Here there are two distinctly different cases to be dealt with separately.

(*a*) The point P_4 in Fig. 1 representing one of the four phases lies inside the triangle formed by the other three P_1, P_2, P_3. In this case only one pattern of coexistence is possible. P_4 may coexist with P_1, P_2, and P_3; the connecting lines P_1P_4, P_2P_4, and P_3P_4 are tie lines. The situation here is analogous to that in binary systems, in that the geometry uniquely determines the phase coexistence pattern.

(*b*) None of the four phases lies inside the triangle formed by the other three. This situation is shown in Fig. 2. Points P_1, P_2, P_3, P_4 represent the four phases. It is seen that P_1 and P_2, P_2 and P_3, P_3 and P_4, P_4 and P_1 may coexist, as they are immediate neighbors. However, the coexistence of P_1 with P_3 excludes the coexistence of P_2 with P_4 and *vice versa*, because these two tie lines intersect each other. Which one of the two mutually exclusive coexistence patterns is actually followed by the system cannot be deduced from *a priori* geometric considerations; it has to be determined by experiment. This is usually accomplished by preparing a sample of the composition P_Z, or near it, allowing the sample to approach equilibrium at the temperature in question, and then identifying the phases present by any suitable technique, such as microscopy, or x-ray diffraction.[2] The sample of composition P_Z is then found to consist of *either* P_1 and P_3 *or* P_2 and P_4. Correspondingly, the quadrangular phase field $P_1P_2P_3P_4$ is divided into two three-phase fields, i.e., either $P_1P_2P_3$ and $P_1P_3P_4$, or $P_1P_2P_4$ and $P_2P_3P_4$ depending on which diagonal is the valid tie line.

Accordingly, ternary systems show considerably more complexity than binary systems regarding the phase coexistence in their univariant equilibria. As a result the behavior of systems with more than three components is not at once apparent. By extrapolation increasing complexity is to be expected with any increase in the number of components.

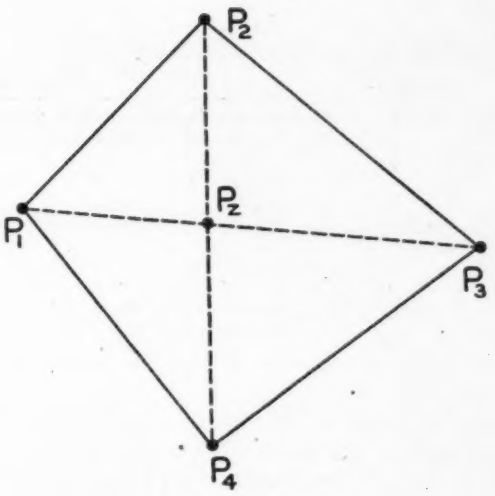

FIG. 2.

The main question to be considered here is to what extent in the general case of n components the coexistence relationships are predetermined by the geometry of the points representing the composition of the various phases. How many possible coexistence patterns are compatible with a given set of phase points in the isothermic section of the n-component system? What is the theoretically required minimum number of samples of different composition that have to be prepared and examined in order to completely determine the phase coexistence relationships at a certain temperature in a given n-component system where the composition of all phases is already known? In order to answer these questions we have to examine the various possible geometric configurations of the phases.

In a system of n components there are $n-1$ independent composition variables. Therefore, the isothermic section of such a system requires $n-1$ dimensions for its description. According to the phase rule, n phases may coexist in a univariant equilibrium. At any temperature the composition of all the n-coexisting phases is uniquely determined (by definition of the univariant equilibrium). As a result each of the n phases will be represented by a single point in the $n-1$ dimensional isothermic section. As long as there are altogether only n phases formed in the system, there is no problem. All n phases may

[2] The procedure described here for determining the coexisting phases in ternary systems was first formulated (as far as the author is aware) by W. Reinders, Zeits. f. anorg. allgem. Chemie **93**, 229 (1915), and by W. Guertler, Metall und Erz **8**, 192 (1920). It was given by Guertler the name "Klaerkreuzverfahren." This procedure can be used, of course, only if the composition of all four phases is, at least approximately, already known.

TABLE I.

Position No.	Relative place of P_{n+1} with respect to $P_1 \cdots P_n$
1)	P_{n+1} lies inside the n-hedron with respect to all faces $f_1 \cdots f_n$.
2)	P_{n+1} lies outside of the n-hedron with respect to 1 face, inside with respect to $n-1$ faces.
.	.
.	.
.	.
$r+1$)	P_{n+1} lies outside of the n-hedron with respect to r faces, inside with respect to $n-r$ faces.
.	.
.	.
.	.
$n-1$)	P_{n+1} lies outside of the n-hedron with respect to $n-2$ faces, inside with respect to 2 faces.
n)	P_{n+1} lies outside of the n-hedron with respect to $n-1$ faces, inside with respect to 1 face.

coexist to form a univariant equilibrium. The characteristic problems with which we are concerned arise if the number of phases formed in the system is larger than the maximum number (n) which the phase rule allows to coexist in a univariant equilibrium.[3] The following geometric considerations will, therefore, have to deal with the various possible geometric configurations of $n+1$ points in $n-1$ dimensional space.

GEOMETRIC CONSIDERATIONS

In $n-1$ dimensional Euclidean space let, points $P_1, P_2 \cdots P_n$ be given so that any k points (where $k \leq n$) will set up a $(k-1)$-dimensional k-hedron. This amounts to the exclusion of degenerate cases where a set of k points is contained in a $(k-2)$-dimensional flat.

$P_1 \cdots P_n$ set up an $(n-1)$-dimensional n-hedron, which has n faces.[4] These faces are $(n-2)$-dimensional hyperplanes and each contains $n-1$ of the n points. To each point P_k corresponds a face f_k which contains all of $P_1 \cdots P_n$ except P_k. Each $(n-2)$-dimensional face (including its extension to infinity) f_k divides the $(n-1)$-dimensional space into two half spaces; I. the half space which contains P_k, and II. the other half space. All points P_I of I will be termed in the following: points "inside the n-hedron with respect to f_k;" all points P_{II} of II will be termed: points "outside the n-hedron with respect to f_k."

All points P_I are on the same side of f_k as P_k (symbol: P_I, P_k—f_k) which means that the straight connecting line of P_I and P_k intersects f_k at a point P_a lying outside of the interval $P_I P_k$. All points P_{II} (outside of the n-hedron with respect to f_k) are on the side of f_k away from P_k (symbol: P_{II}—f_k—P_k). This means that the straight line connecting P_{II} and P_k intersects f_k at a point P_b lying between P_{II} and P_k; f_k separates P_{II} from P_k.

Let us now examine the different possible variations if a new point P_{n+1} is introduced, which is not contained in any one of faces $f_1 \cdots f_n$. In relation to the n-hedron of $P_1 \cdots P_n$ the additional point P_{n+1} may occupy one of the possible positions exhaustively classified in Table I.

No matter which position P_{n+1} occupies, however, the points $P_1 \cdots P_{n+1}$ form a structure which may be called an $(n-1)$-dimensional or flat $(n+1)$-hedron. Such an $(n+1)$-hedron has $[(n+1) \cdot n]/2$ "faces," each of which contains $n-1$ of the total of $n+1$ points. To each pair of points P_i, P_j corresponds a face which contains all points $P_1 \cdots P_{n+1}$ except P_i and P_j. This face may be designated by the symbol: $f_{i,j}$. It is obvious that in this new nomenclature the faces previously marked $f_1 \cdots f_n$ will be designated $f_{1,n+1} \cdots f_{n,n+1}$ since none of them contains P_{n+1}. They constitute the "family of faces" corresponding to P_{n+1}.

If we examine the different relative positions which two points P_i, P_j and the corresponding face $f_{i,j}$ may occupy, we find that two cases are possible: P_i and P_j may lie on the same side of $f_{i,j}$ (symbol: P_i, P_j—$f_{i,j}$) or they may lie on opposite sides (symbol: P_i—$f_{i,j}$—P_j). If P_i and P_j both lie on the same side of $f_{i,j}$ then the $(n+1)$-hedron has no point on the other side of $f_{i,j}$. In this case $f_{i,j}$ is part of the outside "shell" of the $(n+1)$-hedron. However, if P_i and P_j lie on opposite sides of $f_{i,j}$ then $f_{i,j}$ is an "inside face" of the $(n+1)$-hedron.

As each face contains $n-1$ and only $n-1$ of the $n+1$ points (that is, two less than the total number), it is clear that, in general, the intersection of any two faces must contain $n+1-2-2 = n-3$, and only $n-3$, of the total of $n+1$ points. If, however, the two faces belong to the

[3] Equilibria involving critical conditions are not under consideration in the present paper.

[4] The term "face" is used in the following to denote an $n-2$ dimensional hyperplane in $n-1$ dimensional space, containing $n-1$ of the given set of n or $n+1$ points.

same family, like $f_{j,k}$ and $f_{k,i}$, then they will have $n+1-3=n-2$ of the $n+1$ points in common. Two faces divide the $(n-1)$-dimensional space into four segments, so that a point of one of these segments is separated from a point of another segment by at least one of the two faces.

Any three faces have, in general, $n+1-2-2-2=n-5$ of the $n+1$ points in common. But, if each two of the three faces belong to a family, then the $n-2$ points contained in any two faces will be shared by all three. Thus faces $f_{1,2}$, $f_{2,3}$, and $f_{3,1}$, which may be said to form a "cyclic group," have in common points P_4, $P_5 \cdots P_{n+1}$, whereas point P_1 is contained only by $f_{2,3}$, P_2 only by $f_{1,3}$ and P_3 only by $f_{1,2}$. The three $(n-2)$-dimensional faces belonging to such a "cyclic group" have a common $(n-3)$-dimensional intersection set up by their common $n-2$ points. In such a "cyclic" case any one of the three faces passes through two opposite segments only of the four into which $(n-1)$-dimensional space is divided by the other two faces. This differs from the general case of three intersecting faces not forming a cyclic group, where any face passes through all four segments of space cut by the other two faces.

Let us now consider position No. $(r+1)$ of the above classification for P_{n+1}. Here P_{n+1} lies inside the n-hedron with respect to $n-r$ faces of the n-hedron $P_1 \cdots P_n$. Let $f_{i,n+1}$ and $f_{k,n+1}$ be two of these $n-r$ faces. Face $f_{i,k}$ contains P_{n+1} by definition. The three faces: $f_{i,n+1}$, $f_{k,n+1}$, and $f_{i,k}$ form a "cyclic group," as described above, and they have a common intersection of

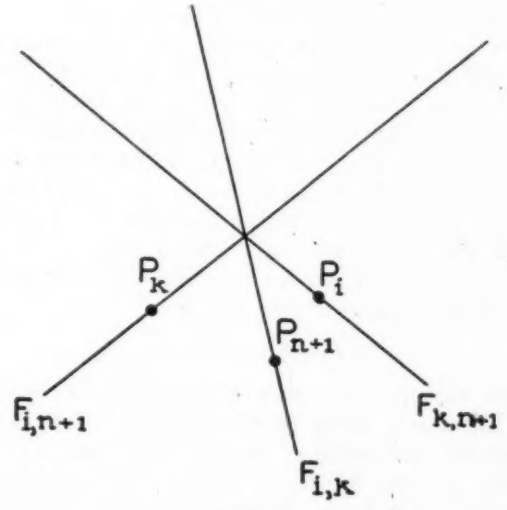

FIG. 3.

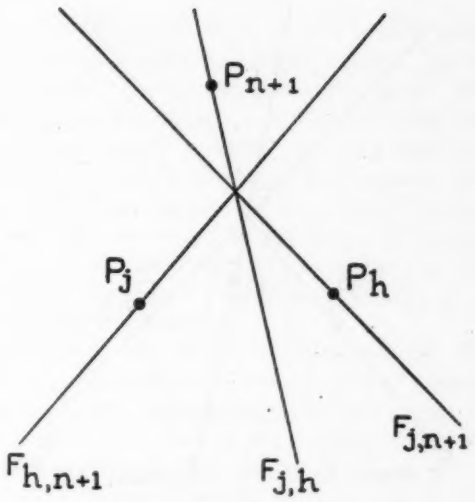

FIG. 4.

$n-3$ dimensions, containing $n-2$ of the $n+1$ points. Each of these three faces contains one, and only one, of the points P_i, P_k, P_{n+1}. The above definition of $f_{i,n+1}$ and $f_{k,n+1}$ implies that: P_i and P_{n+1} lie on the same side of $f_{i,n+1}$:

$$P_i, P_{n+1} — f_{i,n+1}, \tag{1a}$$

and that P_k and P_{n+1} lie on the same side of $f_{k,n+1}$:

$$P_k, P_{n+1} — f_{k,n+1}. \tag{1b}$$

It is easily seen that P_{n+1} must lie in that segment of space between P_i and P_k. Consequently, $f_{i,k}$ which contains P_{n+1} but neither P_i nor P_k, must pass *between* P_i and P_k and separate them. This is immediately obvious when the two dimensional plane is considered which contains all three: P_i, P_k, and P_{n+1}. (See Fig. 3.) Here $F_{i,n+1}$, $F_{k,n+1}$, and $F_{i,k}$ are the intersection lines of this plane with hyperplanes $f_{i,n+1}$, $f_{k,n+1}$, and $f_{i,k}$. If P_i and P_k obey conditions (1a) and (1b), $F_{i,k}$ must separate P_i and P_k in our plane. These mutual positions, however, remain the same if the arrangement is again viewed in $(n-1)$-dimensional space. Consequently the relationship of $f_{i,k}$, P_i and P_k is as follows:

$$P_i — f_{i,k} — P_k. \tag{1}$$

Similarly, let $f_{j,n+1}$ and $f_{h,n+1}$ be two of the r faces with respect to which P_{n+1} lies outside the n-hedron $P_1 \cdots P_n$. Due to this definition, P_j and P_{n+1} lie on opposite sides of $f_{j,n+1}$:

$$P_j — f_{j,n+1} — P_{n+1}, \tag{2a}$$

and P_h and P_{n+1} lie on opposite sides of $f_{h,n+1}$:

$$P_h — f_{h,n+1} — P_{n+1}. \tag{2b}$$

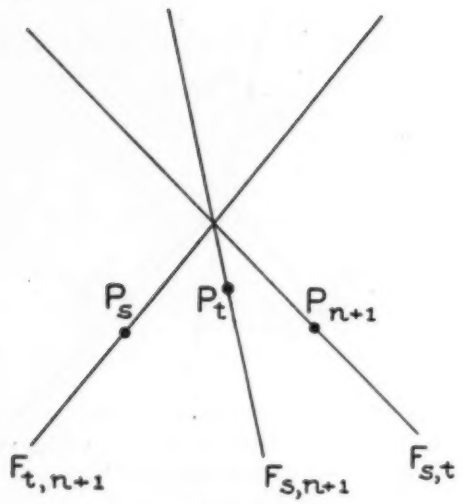

FIG. 5.

Obviously, P_{n+1} must lie in that segment of space opposite to both P_j and P_k. Consequently, $f_{j,k}$, which contains P_{n+1} but neither P_j nor P_k, must also pass through this segment. However, $f_{j,k}$ extends over its common intersection with $f_{j,n+1}$ and $f_{k,n+1}$ into the opposite segment, which lies between P_j and P_k, and it separates these two points. This can be again directly seen in the two-dimensional plane containing P_j, P_k, and P_{n+1} (Fig. 4), and it remains true in $(n-1)$-dimensional space. Therefore, if P_j and P_k obey conditions (2a) and (2b), their relationship with $f_{j,k}$ is as follows:

$$P_j—f_{j,k}—P_k. \tag{2}$$

In analogy to relations (1) and (2), the following third relation[5] can also be deduced (Fig. 5):

$$\text{if } P_s—f_{s,n+1}—P_{n+1}, \tag{3a}$$

$$\text{and } P_t,\ P_{n+1}—f_{t,n+1}, \tag{3b}$$

$$\text{then } P_s,\ P_t—f_{s,t}. \tag{3}$$

Let us now select from among $P_1 \cdots P_n$ all points P_x for which

$$P_x—f_{x,n+1}—P_{n+1}. \tag{I}$$

It then follows from (2a), (2b), and (2) that the relationship between any two points of this group is the same as that between any one of them and P_{n+1}. We may therefore consider P_{n+1} as a member of this group which is defined by relation (I) (Group I).

The relationship of P_{n+1} with the remaining points P_y of $P_1 \cdots P_n$ is

$$P_y,\ P_{n+1}—f_{y,n+1}, \tag{II}$$

it follows from (1a), (1b), and (1) that the relationship between any two points of this group is the same as between any two points of Group I. The group of points now under consideration (Group II as defined by relation II) does, of course, not contain P_{n+1}.

It follows from (3a), (3b), and (3) that the relationship of any point of Group I with any point of Group II is the same as that of P_{n+1} with any point of Group II. Consequently, if any other point of Group I would be used as a starting point instead of P_{n+1}, the resulting grouping of points $P_1 \cdots P_n$ into Groups I and II would remain unchanged. It can be readily seen that the same is also true for the use of any point of Group II as a starting point, although in this case the designation of Groups I and II would be reversed. The grouping of points $P_1 \cdots P_{n+1}$ into two mutually exclusive groups depends, therefore, only on their geometry, and it is independent of the selection of the one to be designated as P_{n+1}.

Summarizing the foregoing considerations: any set of points $P_1 \cdots P_{n+1}$ given in $(n-1)$-dimensional space so that any k points (where $k \leq n$) will set up a $(k-1)$-dimensional k-hedron can be divided into two groups in such a way that any two points of one group lie on opposite sides of the hyperplane containing the other $n-1$ points, but any two points selected from *both* groups (one from each) lie on the same side of the hyperplane containing the other $n-1$ points.

If P_{n+1} is in position $(r+1)$, that is, it lies "outside" with respect to r faces (see Table I), then the r points P_j for which:

$$P_j—f_{j,n+1}—P_{n+1}$$

form Group I together with P_{n+1}; $r+1$ points in all. Each point in Group I is in the same position, in relation to the n-hedron of the other points, as P_{n+1}; it lies "outside" with respect to r faces. The $n-r$ points P_i corre-

[5] It is noted that relations (1)–(3) are analogous to the algebraic relations in multiplication of positive and negative numbers:

if a is negative,	(1a)
and b is negative,	(1b)
then $a \cdot b$ is positive;	(1)
and	
if a is positive,	(2a)
and b is positive,	(2b)
then $a \cdot b$ is positive;	(2)
and	
if a is negative,	(3a)
and b is positive,	(3b)
then $a \cdot b$ is negative.	(3)

TABLE II.

Configuration no.	Position* of points in Group I	Position* of points in Group II	Number of points in Group I	Number of points in Group II
1.)	No: 1	No: n	1	n
2.)	No: 2	No: $n-1$	2	$n-1$
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
$r+1$.)	No: $r+1$	No: $n-r$	$r+1$	$n-r$
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
k.)	No: k	No: $n-k-1$	k	$n-k-1$

* Refers to Table I.

sponding to the $n-r$ faces with respect to which P_{n+1} lies "inside"

$$P_i, P_{n+1}—f_{i,n+1}$$

form Group II. For each one of the $n-r$ points of Group II there are $n-r-1$ faces with respect to which it lies "outside," corresponding to the $n-r-1$ other points of Group II. This is so since

$$P_i—f_{i,k}—P_k$$

for any two points P_i and P_k of Group II as well as for any two points of Group I.

For a given set of $n+1$ points the number of faces with respect to which one of these points lies outside the n-hedron of the other n points will be found either r or $n-r-1$ according to which group the investigated point happens to belong. The designation of Group I and Group II may be reversed, but the geometric configuration of the $n+1$ points remains the same. Therefore, the positions designated as $r+1$) and $n-r$) in Table I actually represent the *same* geometric configuration viewed from different angles. As a result, there are only k different configurations as shown in Table II, where $k=n/2$ if n is an even number, and $k=(n+1)/2$ if n is an odd number.

It is to be noted (see Table I) that configuration No. 1 is very different from the others in that one point lies inside the n-hedron of the other n points (it lies inside with respect to all faces of the n-hedron), and the shell of the $(n+1)$-hedron degenerates into an n-hedron. In all other configurations the shell is an $(n+1)$-hedron, and there is no inside point.

In the general case of configuration No: $r+1$ all the $[(n-r)\cdot(n-r-1)]/2$ "inside faces," each of which separates two of the $n-r$ points of Group II, contain all points of Group I (because the only two of the $n+1$ points which such a face does not contain are both Group II points). Furthermore, these are the only faces which contain all points of Group I. Not all these inside faces are necessary, however, to fully determine, by their intersection, the r-dimensional linear space H_{I} containing the $r+1$ points of Group I. Such an r-dimensional linear space is uniquely fixed in $(n-1)$-dimensional space by the intersection of only $n-r-1$ faces (a face is an $(n-2)$-dimensional hyperplane).

Vice versa, the $n-r-1$ dimensional linear space H_{II} containing the $n-r$ points of Group II is fixed by the intersection of only r out of a total number of $[(r+1)\cdot r]/2$ inside faces, each of which separates two points of Group I.

Let us examine now the intersection of linear space H_{I} set up by all Group I points with linear space H_{II} set up by all Group II points. Since H_{I} represents the intersection of $n-r-1$ faces and H_{II} represents the intersection of r faces, the intersection of H_{I} with H_{II} is determined by the intersection of $n-r-1+r=n-1$ faces. The intersection of $n-1$ independent $(n-2)$-dimensional hyperplanes in $(n-1)$-dimensional space is a point.

It follows, then, that the linear space set up by the $r+1$ points of Group I and the linear space set up by the $n-r$ points of Group II have one point, and only one point, in common. As all faces involved are inside faces, this intersection point P_Z will be inside the $(n+1)$-hedron and also inside the $(r+1)$-hedron of Group I points and inside the $(n-r)$-hedron of Group II points.

If the coordinates of the $n+1$ points $P_1 \cdots P_{n+1}$ are given, and the division of these points into Groups I and II is known, the coordinates of the intersection point P_Z can be calculated by well-known analytical methods.

COEXISTENCE OF PHASES IN UNIVARIANT EQUILIBRIA

As the maximum number of phases coexisting in a univariant equilibrium of n components is n, the problem of the coexistence relationships between $n+1$ phases is resolved into the geometric question of how the $(n+1)$-hedron of the phase points can be divided into a system of smaller n-hedra which are consistent with each other, i.e., which do not intersect.

The foregoing geometric considerations show that the various possible arrangements of the points representing $n+1$ phases in the isothermic section of an n-component system fall into two

main divisions in analogy to the two cases described for ternary systems in the Introduction:

(*a*) One phase point lies inside the n-hedron of the other n phase points (configuration No. 1 in Table II). In this case the composition corresponding to the "inside phase" can be produced by mixing together the n "outside phases" in the correct proportions. This "inside phase" may coexist with all the other n phases. *The coexistence pattern is uniquely determined by the geometry alone.* The phase field enclosed by the n-hedron of the "outside phases" is divided into n smaller n-hedra, each of which represents the isothermic section of a univariant n-phase equilibrium. It is notable that the "inside phase" takes part in all univariant equilibria of the system at the temperature in question. In this case, if the composition of the $n+1$ phases is known, it is possible to predict for any sample of known composition the phases which it will contain, without any further experimental work. The analogy with case (*a*) of the ternary systems (see Introduction) is complete.

(*b*) No phase point lies inside the n-hedron of the other n phase points. This case may be subdivided into $k-1$ variants corresponding to the configurations possible for the $n+1$ phase points (configurations 2 to k in Table II). However, in all these variants the participating $n+1$ phase points can be divided into two separate groups in such a way that the $(n-r)$-hedron corresponding to the $n-r$ points of Group II and the $(r+1)$-hedron corresponding to the $r+1$ points of Group I intersect at a point P_Z which lies inside the $(n+1)$-hedron as well as inside the $(r+1)$-hedron and the $(n-r)$-hedron in question. The various subdivisions under case (*b*) differ only in the value of r which may be any integer between 2 and k, where $k=n/2$, if n is an even number and $k=(n+1)/2$ if n is an odd number (configurations Nos. 2 to k in Table II).

Common to all variants of case (*b*) is that the composition corresponding to the above-mentioned intersection point P_Z can be produced in *two different* ways by mixing from some of the participating phases, namely, *either* from the phases of Group I alone *or* from the phases of Group II alone. If a sample of this composition is prepared, it may contain either the one or the other set of phases. Which set of phases it will be actually composed of *cannot* be predicted on the basis of geometry (i. e., on the basis of the composition of the participating phases) alone. However, if the experimental determination shows that P_Z consists of the phases of Group I, i.e., that these phases may coexist, then the coexistence of the phases of Group II is automatically excluded, and *vice versa*. The coexistence of any phase of Group I with any phase of Group II is uncontested since they are all immediate neighbors (no point of Group I is separated from any point of Group II by the hyperplane containing the other $n-1$ points; see section entitled Geometric Considerations). As a result, the coexistence relationships of $n+1$ phases are completely clarified as soon as it is determined whether the phases of Group I or the phases of Group II may coexist. The $(n+1)$-hedron of all phases will be divided into smaller n-hedra representing univariant equilibria in either one of two ways depending on whether the $(n-r)$-hedron of Group I phases or the $(r+1)$-hedron of Group II phases corresponds to a system of valid tie-lines.

It is clear, then, that in case (*b*) *there are always two and only two coexistence patterns compatible with the geometry of the phase points.* Which one of the two mutually exclusive coexistence patterns correctly describes equilibrium conditions at a given temperature can be determined only by experiment. As described for ternary systems in the Introduction, this is done by preparing a sample of the composition of the intersection point P_Z, allowing it to approach equilibrium at the given temperature, and then identifying the phases present by means of a suitable technique, such as microscopy or x-ray diffraction. The sample is then found to contain the phases of *either* Group I *or* Group II.

The analogy of case (*b*) in n-component systems with case (*b*) in ternary systems is quite complete. This result is somewhat surprising in view of the additional complications expected of many-component systems. This analogy even goes to the extent that *in n-component systems, as well as in ternary systems, theoretically only a single well-chosen sample has to be examined for the phases it contains in order to completely clarify the phase coexistence relationships between $n+1$ phases whose composition is already known.*

The main difference between n-component systems and ternary systems is the following: In ternary systems the choice is always between two rather "symmetrical" alternatives. It is either these two phases or the other two phases that may coexist. In n-component systems there are a number of possibilities. The choice is between a group of two phases and a group of

$n-1$ phases, or a group of three phases and a group of $n-2$ phases, and so forth, depending on which variant of case (*b*) we happen to be dealing with, that is, in which one of the above described configurations Nos. 2, $3\cdots k$ our $n+1$ phase points happen to be arranged. Table III gives a list of these variations.

TABLE III.

Configuration no. of $n+1$ phase points (reference Table II)	A sample of the composition Pz may consist of the following number of phases in equilibrium:	
	Either	*Or*
2.)	2	$n-1$
3.)	3	$n-2$
.	.	.
.	.	.
.	.	.
$r+1$	$r+1$	$n-r$
.	.	.
.	.	.
.	.	.
k	k	$n-k+1$

where $k=n/2$ or $k=(n+1)/2$ depending on whether n is even or odd.

NON-VARIANT EQUILIBRIA

The results obtained above for univariant equilibria can be further utilized to arrive at a general classification of the different types of non-variant equilibria possible in n-component systems.

At the singular temperature of the non-variant equilibrium all $n+1$ phases coexist, but at temperatures just above or just below that the conditions described in the previous section prevail: the $(n+1)$-hedron is divided into a system of n-hedra corresponding to univariant equilibria. The following cases of non-variant equilibria are possible:

(*a*) One phase point lies inside the n-hedron of the other phase points. (Configuration No. 1 in Table II.) In this case the "inside phase" extends only above or only below the non-variant temperature. If it extends above, it forms at those temperatures n separate univariant equilibria with the other phases, as described in the previous chapter. At temperatures below the non-variant equilibrium the "inside phase" does not exist: the n other phases form a univariant equilibrium. This situation can be adequately described by saying that the "inside phase" decomposes at the non-variant temperature into the other n phases. The analogy with the eutectic or eutectoid equilibria in binary and ternary systems is complete. Similarly, if the "inside phase" extends toward lower temperatures the conditions in the n-component system are analogous to the peritectic or peritectoid equilibria in binary and ternary systems.

(*b*) No phase point lies inside the n-hedron of the other phase points. At the non-variant temperature all $n+1$ phases coexist. But the $n+1$ phase points can be divided into two groups, and at a temperature just above or just below the non-variant temperature only the phases of Group I or only those of Group II may coexist, as seen in the previous chapter. It is obvious that if one of these coexistence patterns is valid above the non-variant temperature, the other one will be valid below it. Only thus can *both* be valid at the non-variant temperature. In this case all $n+1$ phases extend both above and below the non-variant temperature. The only change taking place at that temperature is the switching over from one of the two coexistence patterns compatible with the geometry of the phase points into the other one. This change could be also described as an abrupt rearrangement of the tie-lines at the non-variant temperature.

Although there is no similar equilibrium in binary systems, this "rearrangement" or "transition" type of non-variant equilibrium is well known in ternary systems. The analogy is quite complete. The difference is that in n-component systems, unlike ternary systems, there are several variants according to the number of phases in the two groups. (See configurations 2 to k in Table III.)

Considering the increased complexity of non-variant equilibria in ternary as against binary systems, it is surprising to find that, as the number of components increases over three, no further complications arise.[6] The two familiar types of non-variant equilibria occurring in ternary systems are the only ones found in systems of many components.

[6] Like in the previous chapter on univariant equilibria, here, too, equilibria involving critical phases are disregarded.

The Production and Decomposition of Ozone by Low Pressure Mercury Vapor Lamps

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A photo-tube method for measuring the concentration of ozone is described. Measurements were made of the rate of production and rate of decomposition of ozone in oxygen and in air by low pressure mercury vapor lamps. The production in oxygen is enhanced by the presence of nitrogen. Increasing the moisture content of the gas decreases the rate of production and increases the rate of decomposition. A new germicidal lamp enclosed in a 10-liter glass tube will form an equilibrium concentration of 145 parts per million by volume. A quartz lamp under the same conditions will form 640 parts per million. With oxygen flowing through the tube the yield for the quartz lamp is 2.5×10^{-3} g ozone/min. or 10 g kw hr.

THE photochemistry of ozone has been the subject of numerous investigations.[1,2,3] Ewell[4] has recently made measurements which make it possible to predict ozone yields from certain types of ultraviolet lamps with considerable accuracy. The purpose of this investigation was to obtain additional information on the production and decomposition of ozone in confined spaces by low pressure mercury vapor arcs.

The lamps used were of the same construction as 15-watt fluorescent lamps; 1″ in diameter and 18″ long, operating at approximately 0.27 amp with an arc drop of 60 volts. One lamp was of quartz; the others were standard germicidal lamps of 9741 Corning glass. The transmission of 1 mm of this glass is 65 percent at 2537A and 4 percent at 1849A.

About 90 percent of the visible and ultraviolet energy radiated by the germicidal lamps is in the 2537A line. A small amount of energy, which decreases with the age of the lamp, is also radiated at shorter wave-lengths, chiefly 1849A. The quartz lamp radiates considerably more energy in this region than the germicidal lamps. The output of 2537A radiation from the lamps was about 3 watts.

The apparatus used is shown in Fig. 1. It consisted of a Pyrex tube 6″ in diameter and 24″ long in which the lamps were supported somewhat off center on a glass cradle. The tube was closed by an end plate which was waxed on and was given a rough exhaust by an oil pump. A stirring device driven from outside of the tube by a magnet insured thorough mixing of the gas. All exposed metal surfaces except for the lead-in wires and the lamp bases were coated with paraffin. The net volume of the tube was 10 liters.

A pair of quartz windows were placed opposite each other near one end of the tube. The absorption of 2537A radiation in the 6″ path between the windows was used as a measure of ozone concentration. For this purpose a germicidal lamp outside of the tube placed close to one window served as a source and an FJ405 photo-tube in front of the other as a detector of radiation. The intensity of visible radiation from the lamp is small compared with the ultraviolet radiation, and the response of the photo-tube to visible is small compared with the response to ultraviolet. The result is that 93 percent of the photo-current is caused by 2537A radiation.

The ultraviolet source for the photo-tube was operated from a constant voltage transformer and was shielded from draughts. Its output was checked by a second FJ405 photo-tube and when necessary corrections for drift in its ultraviolet output were made.

The ozone concentration was calculated from the photo-current by Beer's law

$$i/i_0=\epsilon^{-\alpha cd}=\epsilon^{-0.0042c}$$

where

i_0 = photo-current for 0 concentration of ozone,
i = observed photo-current,
α = absorption coefficient $=276\times10^{-6}$ cm^{-1}, [5]
c = ozone concentration in parts per million by volume (p.p.m.),
d = length of path in cm.

With a 6″ light path, concentrations between 10 and 700 parts per million (p.p.m.) by volume, corresponding to values of i/i_0 of 0.96 and 0.056, respectively, could easily be measured.

As a check, two chemical determinations were made by bubbling the contents of the tube

[1] G. S. Forbes and L. S. Heidt, J. Am. Chem. Soc. **56**, 1671, 2365 (1934).
[2] L. S. Heidt, J. Am. Chem. Soc. **57**, 1710 (1935).
[3] Briner and Papazian, Helv. Chim. Acta. **25**, 892 (1942).
[4] A. W. Ewell, J. App. Phys. **13**, 759 (1942).
[5] R. Ladenburg, J. Opt. Soc. Am. **25**, 259 (1935).

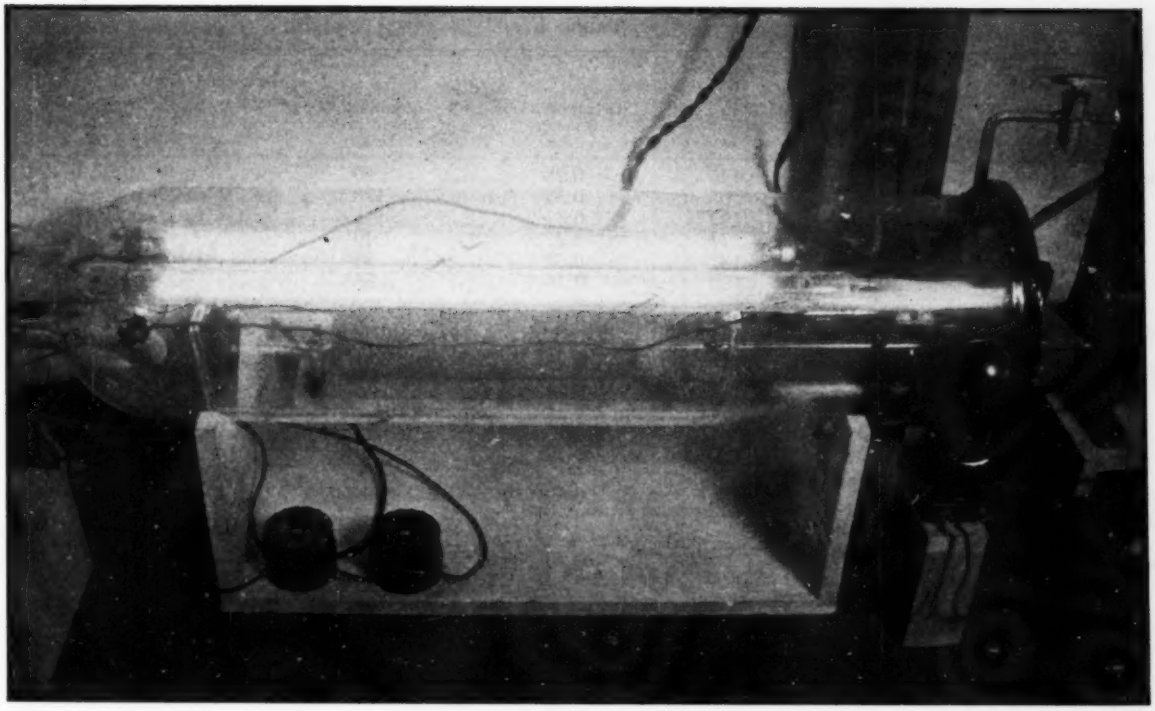

FIG. 1. Ozone generating apparatus.

through KI solution and titrating with sodium thiosulphate. The concentrations determined by the optical method were 90 and 96 percent, respectively, of the chemically determined values.

The gas used was dried by passing slowly through a P_2O_5 drying tube. Some tests were made in which the gas was also passed through a liquid-air trap. No noticeable effect was produced by this additional drying.

Figure 2 shows the results of a typical run with a quartz lamp in dry oxygen. Curve *A* gives the ozone concentration as a function of time at 1 minute intervals after turning on the lamp. In this case a limiting concentration of 530 p.p.m. was reached in 15 minutes.

Let us assume that ozone is produced at a constant rate and that the decomposition is a monomolecular reaction, then

$$dc/dt = m - kc, \tag{1}$$

and

$$c = c_\infty(1 - e^{-kt}), \tag{2}$$

where

c = concentration in parts per million,
$c_\infty = m/k$ = concentration when equilibrium is reached,
m = rate of formation in parts per million per minute,
k = velocity constant per minute.

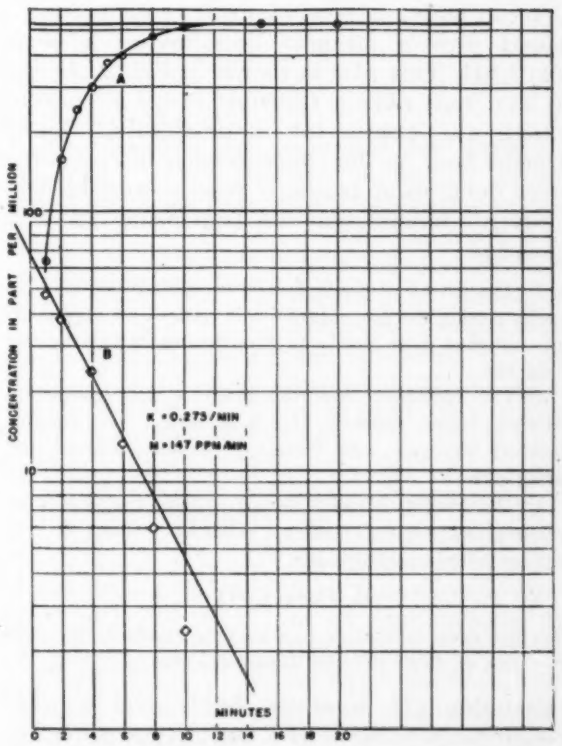

FIG. 2. Formation of ozone in dry oxygen by quartz lamp.

TABLE I.

Gas	Quartz lamp: Equilibrium concentration c_∞	Quartz lamp: Rate of formation m	Quartz lamp: Decomposition constant k	Germicidal lamps: Equilibrium concentration c_∞	Germicidal lamps: Rate of formation m	Germicidal lamps: Decomposition constant k
Dry oxygen	530	147	0.28	90	8	0.09
	560	205	0.37	128	15	0.11
	610	192	0.32	145	15	0.10
	640	172	0.27	40*		0.09*
	550	187	0.34	54*		0.13*
	500	180	0.36	56*		0.13*
Average	578	181	0.32	86	13	0.11
Oxygen at 55 percent Relative humidity	270	135	0.50			
	270	120	0.44			
	250	137	0.55			
Average	263	131	0.50			
Oxygen at 100 percent Relative humidity	230	136	0.59			
Dry air	450	90	0.20	18*		0.16*
	500	115	0.23	25*		0.09*
				30*		0.15*
Average	475	103	0.22	24		0.13
Air at 100 percent Relative humidity	53	34	0.64			

* These tests were made about two weeks later than the other tests included in the table and after the germicidal lamp had been used for 3 hours.

Accordingly, a plot of $\log (c_\infty - c)$ against t should give a straight line having a slope $= k/2.303$. This plot is shown in Fig. 2. It can be seen that over a threefold range in concentration the points fall approximately on a straight line. As the concentration increases the curve deviates increasingly from a straight line.

Several factors may be responsible for this deviation:

(1) The output of the lamp is not constant but changes rapidly during the first minute as it comes up to temperature and then more slowly as it warms up during the rest of the run.

(2) The radiation from the lamp is not completely absorbed before reaching the tube walls. The amount absorbed increases with increasing ozone concentration during a run.

(3) The assumption of a monomolecular reaction is an oversimplification of the process. While the primary decomposition process probably is

$$O_3 + h\nu = O_2 + O$$

other processes take place to a varying extent as the concentration of ozone changes during the run.

Equation (2), however, holds over a wide enough range to serve as a useful approximation under the experimental conditions of this investigation.

The first section of Table I gives values of k and m obtained in several runs with dry O_2.

The variation in successive runs may be caused by differences in the condition of the tube wall since it was not baked out and was given only a rough exhaust.

The radiation is practically the sole cause of decomposition in these tests. When the tube was filled with ozone at a concentration of 500 p.p.m. and allowed to stand in the dark, the decomposition constant was 0.00077/min, corresponding to a half-life of 15 hr. This decay rate is negligible compared with the effect of the lamp.

Two runs with the germicidal lamp in dry oxygen are shown in Fig. 3. For curve A the procedure was the same as curve A in Fig. 2. Curve B, Fig. 3, shows the results of a run with the same germicidal lamp where the equilibrium was approached from the side of high concentration. In this case a high concentration of ozone was formed by running the quartz lamp until equilibrium was reached at 580 p.p.m. The quartz lamp was then turned off and the germicidal lamp turned on. The concentration dropped slowly towards an equilibrium value of 128 p.p.m., which is in fair agreement with the value of 145 p.p.m. obtained when the equilibrium was

approached from the other side. The constants

$$k = 0.10/\text{min.},$$
$$m = 15 \text{ p.p.m./min.}$$

are small compared with those for the quartz lamp.

This was a new lamp having an output of 2537A radiation of about 3.1 watts. Since this was practically the same as the 2537A output of the quartz lamp, the difference in performance must be attributed to the larger output of 1849A radiation from the latter.

The above value represents the maximum rate of formation for germicidal lamps. The lamps age rapidly and after a short period of operation the output of 1849A radiation is greatly reduced. This is illustrated in Table 1 by the marked decrease in equilibrium concentration after a few hours of operation.

Table I also gives the results of measurements on wet oxygen and dry and wet air. Increasing the moisture content of oxygen to 55 percent relative humidity produces a marked drop in the rate of formation and an increase in the rate of decomposition resulting in a 50 percent decrease in equilibrium concentration. The effect of further increase in moisture content is small.

The rate of formation and the decomposition constant in dry air are both less than in dry oxygen, resulting in an equilibrium concentration of about 80 percent of that for oxygen. The effect of moisture is much greater on the rates in air than in oxygen. Thus the equilibrium concentration in wet air is only about 10 percent of the value for oxygen.

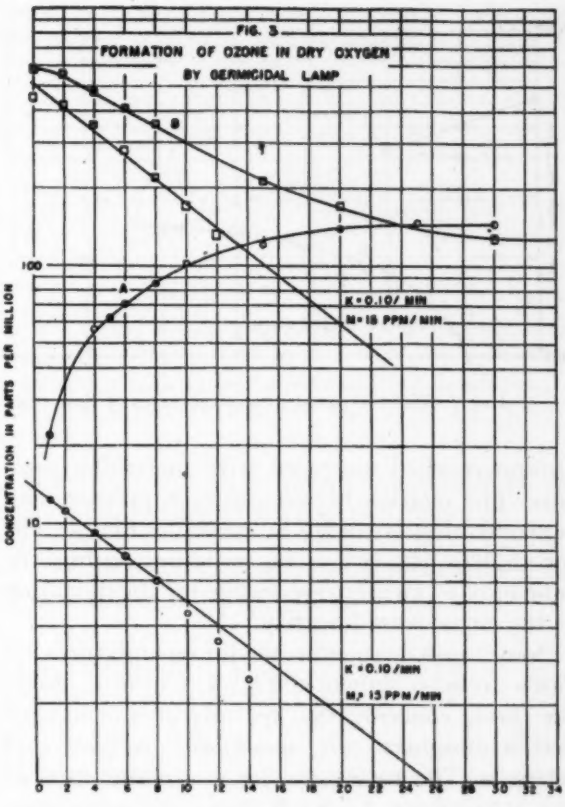
FIG. 3
FORMATION OF OZONE IN DRY OXYGEN
BY GERMICIDAL LAMP
CONCENTRATION IN PARTS PER MILLION
100
10
A
K = 0.10/ MIN
M = 15 PPM/ MIN
K = 0.10 /MIN
M = 15 PPM/MIN
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34

FIG. 3.

Decomposition constants only are given for the germicidal lamp since the concentration of ozone was too low for reliable measurements of the rate of formation. The decomposition rates were obtained by first forming high concentrations with the quartz lamp.

A series of measurements was made on the effect of pressure using dry oxygen at pressures from 1 atmosphere down to 45 mm. Within the limits of error of the experiment the decomposition rate was independent of pressure. However, the rate of formation and hence the final concen-

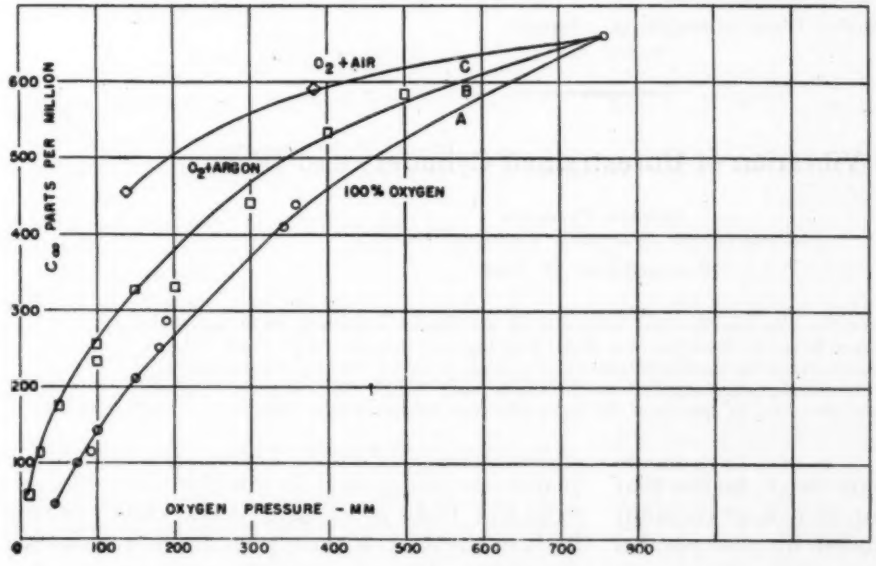

FIG. 4. Ozone concentration as a function of oxygen pressure. Quartz lamp.

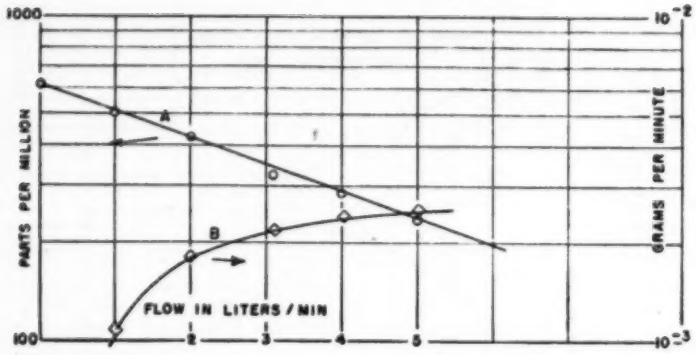

FIG. 5. Yield of ozone at various rates of flow of oxygen.

tration reached increased with increasing pressure. The relation between oxygen pressure and concentration is shown in curve *A*, Fig. 4. The incomplete absorption of radiation within the tube may be largely responsible for the deviation of the curve from linearity.

Some measurements made on mixtures of gases are also shown in Fig. 4. Curve *C* shows the ozone concentration for mixtures of oxygen and atmospheric air, essentially oxygen and nitrogen. The total pressure was maintained at one atmosphere. Curve *B* shows the ozone concentration for mixtures of oxygen and argon, also at one atmosphere. The argon used contained 15 percent of nitrogen. A comparison of curves *B* and *C* shows that the ozone yield for a given pressure of oxygen is enhanced by the presence of the nitrogen. While oxides of nitrogen may be formed under these conditions, their absorption for 2537A radiation is negligibly small compared with ozone.

The larger yields shown by *B* and *C* over that for *A* may be in part caused by the increase in pressure.

Measurements of the ozone yield were also made at various rates of flow of dry oxygen through the tube. Curve *A*, Fig. 5 shows the concentration of O_3 as a function of the rate of flow and curve *B* shows the total yield in g/min. as a function of the rate of flow. The yield increases as the rate of flow is increased because the more rapid removal from the illuminated zone affords less opportunity for decomposition by the radiation. The yield reaches a limiting value of 2.5×10^{-3} g/min. at a rate of flow of 2 liters per minute. This corresponds to a yield of 10 g/kw hr. The maximum theoretical yield calculated from the value of $m=181$ (obtained under static conditions) is 3.9×10^{-3} g/min.

The constants obtained in these tests are representative of the performance of the lamps in confined spaces. As has been shown by Ewell, the equilibrium concentration depends upon the nature and area of the exposed surfaces. Accordingly, calculations for larger spaces based on the values reported here can only set an upper limit to the value which may be obtained.

Although more refined methods would lead to more accurate results, it was felt that the publication of these results would be a useful guide in evaluating the ozone production of low pressure lamps.

Flexural Vibration of Unrestrained Cylinders and Disks

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Solutions are given for the free flexural vibration of a cylinder vibrating as a rod would vibrate and for the free flexural vibration of a disk vibrating as a circular plate would vibrate. The solutions are based upon the mathematical theory of elasticity. Curves are given showing the correction factors which, when applied to the elementary solutions, will give results in agreement with those obtained by means of the more rigorous solutions given here.

ACCORDING to common usage, bodies that are symmetrical about an axis of constant cross section and are bounded by two parallel planes are designated as circular rods, circular cylinders, disks or circular plates, chiefly on the basis of the ratio of their axial to their diametral dimension. The term *circular cylinder* is sometimes applied to any of these bodies, but usually

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a cylinder is considered to be a body in which the axial dimension is greater than the diametral dimension. In this paper when bodies of these types are considered to be vibrating in flexure as a rod would vibrate, they will be designated as cylinders; when they are considered to be vibrating in flexure as a circular plate would vibrate, they will be designated as disks. If the two dimensions are approximately equal, the body may be considered as either a short cylinder or a thick disk, depending on whether its vibration as a rod or as a plate is being investigated. This paper is concerned primarily with the free flexural vibration of cylinders and disks for which the smaller of the two dimensions is at least 20 percent as large as the larger.

The elementary theory of flexural vibration—which neglects the effects of shear on deflection and the effects of rotatory inertia forces—is justifiable for the flexural vibration of slender rods or thin plates. But for the bodies considered in this paper the formulas based on the elementary theory may be in considerable error. (For very high modes of vibration such that the wave-length is not large compared to thickness, shear and rotation would have to be considered for slender rods and thin plates. After a brief discussion of the equations that are based upon the elementary theory, equations based upon the mathematical theory of elasticity will be derived. So far as is known, these derivations have not been previously published.[1]

According to the elementary theory the resonant frequencies of flexural vibration for a slender rod are given by

$$f=(m^2a/4\pi l^2)(E/\rho)^{\frac{1}{2}}, \tag{1}$$

and for a thin plate are given by

$$f=(M^2l/4\pi a^2)(E/3(1-\mu^2)\rho)^{\frac{1}{2}}, \tag{2}$$

where

f is resonant frequency in cycles per unit time,
a is radius,
l is axial dimension,
E is Young's modulus of elasticity,
ρ is mass per unit volume,
μ is Poisson's ratio, and
m and M are constants that depend on the boundary conditions and the modes of vibration.

Equations (1) and (2) are the frequency equations that follow from solutions of the following differential equations, respectively.[2-4]

$$\frac{Er_x^2}{\rho}\frac{\partial^4 v}{\partial z^4}+\frac{\partial^2 v}{\partial t^2}=0, \tag{3}$$

$$\frac{El^2}{12(1-\mu^2)\rho}\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r}\frac{\partial^2}{\partial\theta^2}\right)^2 w+\frac{\partial^2 w}{\partial t^2}=0, \tag{4}$$

where

$r_x=a/2$ is the radius of gyration of the circular cross section,
v, w are the displacements for rod and plate, respectively,
r, θ, z are cylindrical coordinates, and
t is time.

The only boundary condition considered in this paper is that of no external restraint. For no external restraint the constant m in Eq. (1) is a root of $\cos m \cosh m = 1$, which equation may be factored into[5]

$$\left(\tan\frac{m}{2}+\tanh\frac{m}{2}\right)\left(\cot\frac{m}{2}-\coth\frac{m}{2}\right)=0. \tag{5}$$

Values of m, accurate to three decimal places, for the first six modes of vibration are given below:[5]

$$m_1=4.730 \quad m_4=14.137$$
$$m_2=7.853 \quad m_5=17.279$$
$$m_3=10.996 \quad m_6=20.420.$$

For no external restraint M in Eq. (2) is a root of[4]

$$\phi(\mu, n, M)F(\mu, n, iM) = \phi(\mu, n, iM)F(\mu, n, M), \tag{6}$$

where

$$\phi(\mu, n, M)=M^3\frac{\partial}{\partial M}J_n(M)+(1-\mu)n^2\left[M\frac{\partial}{\partial M}J_n(M)-J_n(M)\right],$$

$$F(\mu, n, M)=M^2J_n(M)+(1-\mu)\left[M\frac{\partial}{\partial M}J_n(M)-n^2J_n(M)\right],$$

[1] The resulting frequency equation for the flexural vibration of a cylinder is given without derivation in G. Pickett, "Equations for Computing Elastic Constants from Flexural and Torsional Resonant Frequencies of Vibration of Prisms and Cylinders," A.S.T.M. Preprint No. 47 (1945).

[2] S. Timoshenko, *Vibration Problems in Engineering* (D. Van Nostrand Company, New York, 1937), second edition, p. 332.

[3] A. E. H. Love, *Mathematical Theory of Elasticity* (Cambridge University Press, Cambridge, 1927), fourth edition, pp. 430 and 446.

[4] Lord Rayleigh, *Theory of Sound* (The Macmillan Company, London, 1926), second edition, Vol. 1, pp. 359–360.

[5] S. Timoshenko, see reference 2, p. 343.

J_n = a Bessel function of the first kind and nth rule,
$i = (-1)^{\frac{1}{2}}$.

The various roots of Eq. (6) corresponding to different modes of vibration may be distinguished by subscripts thus: $M_{n,s}$ where n—giving the order of the Bessel functions—signifies the number of nodal diameters and s signifies the number of nodal circles for the mode of vibration considered.

As is evident from Eq. (6), M will also depend on Poisson's ratio.* The seven smallest M's are given below for various values of Poisson's ratio. Note that some M's increase, whereas others decrease with increase in μ. (See Table I.)

If the axial and diametral dimensions are of the same order of magnitude, neglect of the effects of shear and of rotatory inertia, as was done in deriving Eqs. (1) to (4), introduces appreciable error. For example, Eq. (1) for flexural vibration as a rod will give a value 45 percent too high for the resonant frequency for the first mode if the diameter is one-half the length, and the percentage error increases with increase of diameter-to-length ratio. Equation (2) for vibration as a plate will also give a value 45 percent too high for the next to lowest resonant frequency (one nodal circle and no nodal diameter) if the thickness-to-diameter ratio is one-half. For these dimensions Eq. (2) is in error by 35 percent for the lowest resonant frequency (two nodal diameters and no nodal circle).

For flexural vibration as a rod Rayleigh[6] added a term to Eq. (2) to take into account rotatory inertia and Timoshenko[7, 8] added terms to take into account both rotatory inertia and shear. Timoshenko's differential equation is

$$\frac{Er_z^2}{\rho}\frac{\partial^4 v}{\partial z^4}+\frac{\partial^2 v}{\partial t^2}-r_z^2\left(1+\frac{E}{K'G}\right)\frac{\partial^4 v}{\partial z^2\partial t^2}+\frac{r_z^2\rho}{K'G}\frac{\partial^4 v}{\partial t^4}=0, \quad (3a)$$

where

$K'G$ is the factor by which the average shear stress must be divided to obtain the effect of shear on slope and $G=E/2(1+\mu)$ is the modulus of elasticity in shear.

As is shown,[1] the frequency equation based on Eq. (3a) will give results in good agreement with the more exact frequency equation based on the equations of elasticity if K' is given certain values that depend on Poisson's ratio. After this relation between K' and μ has once been established, it appears that the relatively simple frequency equation based on Eq. (3a) will suffice, but in order to establish the relation between K' and μ the more exact frequency equation appears to be necessary and its derivation is therefore given in this paper. So far as is known the terms, corresponding to those added to Eq. (3) by Timoshenko, that should be added to Eq. (4) to take shear and rotatory inertia into account for the flexural vibration of a plate have not been derived. The present writer is of the opinion that it is simpler in this case to solve the problem directly by means of the fundamental equations of elasticity rather than by means of a modification of Eq. (4).

GENERAL SOLUTIONS IN CYLINDRICAL COORDINATES OF THE DIFFERENTIAL EQUATIONS OF VIBRATION

When expressed in the cylindrical coordinates r, θ, z, the differential equations of elasticity for small vibratory motion are the following:[9]

$$\frac{1-\mu}{1-2\mu}\frac{\partial\Delta}{\partial r}-\frac{1}{r}\frac{\partial W}{\partial\theta}+\frac{\partial V}{\partial z}=\frac{\rho}{2G}\frac{\partial^2 u}{\partial t^2},$$

$$\frac{1-\mu}{1-2\mu}\frac{1}{r}\frac{\partial\Delta}{\partial\theta}-\frac{\partial U}{\partial z}+\frac{\partial W}{\partial r}=\frac{\rho}{2G}\frac{\partial^2 v}{\partial t^2},$$

$$\frac{1-\mu}{1-2\mu}\frac{\partial\Delta}{\partial z}-\frac{1}{r}\frac{\partial}{\partial r}(rV)+\frac{1}{r}\frac{\partial U}{\partial\theta}=\frac{\rho}{2G}\frac{\partial^2 w}{\partial t^2},$$

where u, v, w are displacements in the r, θ, z directions, respectively. (Note: The v-displacement in these equations is in the direction of the

TABLE I.

μ	M_{20}	M_{01}	M_{30}	M_{11}	M_{40}	M_{21}	M_{02}
0.0	2.482	2.870	3.736	4.479	4.910	5.952	6.145
0.1	2.432	2.920	3.678	4.495	4.846	5.948	6.166
0.2	2.379	2.963	3.611	4.510	4.769	5.943	6.184
0.3	2.315	3.002	3.526	4.524	4.678	5.939	6.202
0.4	2.247	3.038	3.435	4.539	4.571	5.934	6.219

* This fact is sometimes overlooked as for example the table on page 526 of Marks' *Mechanical Engineers' Handbook*, fourth edition (1941) gives values of M^2 (designated α in the handbook) for various values of n and s without any reference as to the values of μ for which they apply.

[6] Lord Rayleigh, see reference 4, p. 203.

[7] S. Timoshenko, "Vibrations of Bars of Uniform Cross Section," Phil. Mag. [6] **43**, 125–131 (1922).

[8] S. Timoshenko, see reference 2, pp. 337–342.

[9] A. E. H. Love, see reference 3, pp. 288–292.

cylindrical coordinate θ whereas the v-displacement of Eqs. (3) and (3a) is in the direction of the rectangular coordinate y.) t is time.

$$\Delta=\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{1}{r}\frac{\partial v}{\partial \theta}+\frac{\partial w}{\partial z},$$

$$U=\frac{1}{2}\left[\frac{1}{r}\frac{\partial w}{\partial \theta}-\frac{\partial v}{\partial z}\right],$$

$$V=\frac{1}{2}\left[\frac{\partial u}{\partial z}-\frac{\partial w}{\partial r}\right],$$

$$W=\frac{1}{2}\left[\frac{\partial v}{\partial r}+\frac{v}{r}-\frac{1}{r}\frac{\partial u}{\partial \theta}\right].$$

The differential equations of elasticity given above have three fundamental solutions designated (A), (B), and (C) below:[9,10]

$$u=A\frac{a^2}{h}\frac{\partial}{\partial r}J_n\left(\frac{hr}{a}\right)\begin{Bmatrix}\cos \gamma z/a\\ \sin \gamma z/a\end{Bmatrix}^{*}\sin(n\theta+\delta)\cos pt,$$

$$v=A\frac{a^2}{h}\frac{n}{r}J_n\left(\frac{hr}{a}\right)\begin{Bmatrix}\cos \gamma z/a\\ \sin \gamma z/a\end{Bmatrix}\cos(n\theta+\delta)\cos pt, \qquad (A)$$

$$w=A\frac{a\gamma}{h}J_n\left(\frac{hr}{a}\right)\begin{Bmatrix}-\sin \gamma z/a\\ \cos \gamma z/a\end{Bmatrix}\sin(n\theta+\delta)\cos pt;$$

where

$$h^2=\frac{1-2\mu}{2(1-\mu)}\frac{p^2\rho a^2}{G}-\gamma^2,$$

$$u=B\frac{a^2}{k}\frac{\partial}{\partial r}J_n\left(\frac{kr}{a}\right)\begin{Bmatrix}\cos \beta z/a\\ \sin \beta z/a\end{Bmatrix}\sin(n\theta+\delta)\cos pt,$$

$$v=B\frac{a^2}{k}\frac{n}{r}J_n\left(\frac{kr}{a}\right)\begin{Bmatrix}\cos \beta z/a\\ \sin \beta z/a\end{Bmatrix}\cos(n\theta+\delta)\cos pt, \qquad (B)$$

$$w=B\frac{ak}{\beta}J_n\left(\frac{kr}{a}\right)\begin{Bmatrix}\sin \beta z/a\\ -\cos \beta z/a\end{Bmatrix}\sin(n\theta+\delta)\cos pt,$$

where

$$k^2=\frac{p^2\rho a^2}{G}-\beta^2;$$

$$u=C\frac{a^2n}{kr}J_n\left(\frac{kr}{a}\right)\begin{Bmatrix}\cos \beta z/a\\ \sin \beta z/a\end{Bmatrix}\sin(n\theta+\delta)\cos pt,$$

$$v=C\frac{a^2}{k}\frac{\partial}{\partial r}J_n\left(\frac{kr}{a}\right)\begin{Bmatrix}\cos \beta z/a\\ \sin \beta z/a\end{Bmatrix}\cos(n\theta+\delta)\cos pt, \qquad (C)$$

$$w=0,$$

where

$$k^2=\frac{p^2\rho a^2}{G}-\beta^2.$$

[10] L. Pochhammer, "Ueber die Fortpflanzungsgeschwindigkeiten kleiner, Schwingungen in einem unbegrentzen isotropen Kreiscylinder," J. f. reine und angewandte Math. **81–82**, 324–336 (1876–1877).

* Either term within the braces may be used provided that when the upper term is used in the expression for u, the upper term is used in the expression for v, etc.

In the above expressions δ is an arbitrary angle that depends on the line of reference for measurement of θ, $p=f/2\pi$ is the angular frequency, and the factors A, B, and C are arbitrary constants.

In the (A)-solution above either γ or h may be given any arbitrary real, imaginary, or complex value. In like manner in solutions (B) and (C) either β or k may be given any arbitrary value. However, to meet given boundary conditions restrictions must be imposed upon these factors. It is from such restrictions on γ, β, h, and k that the allowable values of p and consequently the frequency f are determined.

As will be demonstrated later for the case of flexural vibration of a cylinder, the requirement of no boundary stresses at the curved surface ($\sigma_r=\tau_{rz}=\tau_{r\theta}=0$ at $r=a$) can be met by a linear combination of all three solutions if β in the (B) and (C) solutions is set equal to γ in the (A)-solution. Unfortunately, this combination results in boundary stresses at the plane surfaces. In a similar manner, as will be demonstrated later, for the case of flexural vibration of a disk, the requirement of no boundary stresses at the plane surfaces ($\sigma_z=\tau_{rz}=\tau_{\theta z}=0$ at $z=\pm l/2$) can be met by a linear combination of solutions (A) and (B) if k in solution (B) is set equal to h in solution (A). But this combination results in boundary stresses at the curved surface.

Apparently, it is not possible by any combination of a finite number of solutions to satisfy rigorously the boundary requirements at both the curved and plane surfaces. Therefore, for practical reasons a choice has to be made. The choice made here, as indicated above, is that the requirement of no boundary stresses at the curved surface will be met for flexural vibration as a rod and the requirement of no boundary stresses at the plane surfaces will be met for flexural vibration as a plate.

The expressions for the six stresses defining the stress at a point in terms of displacements u, v, w and the coordinates r, θ, z are as follows:

$$\sigma_r=2G\left[\frac{\mu}{1-2\mu}\Delta+\frac{\partial u}{\partial r}\right],\quad \tau_{rz}=G\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial r}\right),$$

$$\sigma_\theta=2G\left[\frac{\mu}{1-2\mu}\Delta+\frac{u}{r}\right],\quad \tau_{r\theta}=G\left(\frac{1}{r}\frac{\partial u}{\partial \theta}+\frac{\partial v}{\partial r}-\frac{v}{r}\right),$$

$$\sigma_z=2G\left[\frac{\mu}{1-2\mu}\Delta+\frac{\partial w}{\partial z}\right],\quad \tau_{\theta z}=G\left(\frac{1}{r}\frac{\partial w}{\partial \theta}+\frac{\partial v}{\partial z}\right),$$

where σ_r, σ_θ, σ_z are normal stresses in r, θ, z directions, respectively, and τ_{rz}, $\tau_{r\theta}$, $\tau_{\theta z}$ are shear stresses.

FLEXURAL VIBRATION OF A CYLINDER (FLEXURAL VIBRATION AS A ROD)

The upper terms in the braces of solutions (A), (B), and (C) are applicable for the first, third, fifth, etc., modes of flexural vibration of a cylinder, i.e., symmetrical vibration with respect to the plane midway between the plane surfaces. The lower terms in the braces are applicable for the second, fourth, etc., modes of vibration, i.e., asymmetrical vibration. The integer n is unity for flexural vibration of a cylinder.

When the sum of solutions (A), (B), and (C) is substituted into the expressions for σ_r, $\tau_{r\theta}$, and τ_{rz} and β set equal to γ and r set equal to a, the result for boundary stresses at the curved surface is as follows:

$$\sigma_r=2G\left[A\left(\frac{2J_1(h)}{h}-J_0(h)+\frac{\gamma^2-k^2}{2h}J_1(h)\right)+B\left(\frac{2J_1(k)}{k}-J_0(k)-kJ_1(k)\right)\right.$$
$$\left.+C\left(J_0(k)-\frac{2J_1(k)}{k}\right)\right]\begin{Bmatrix}\cos\gamma z/a\\ \sin\gamma z/a\end{Bmatrix}\sin(\theta+\delta)\cos pt, \quad (7)$$

$$\tau_{r\theta}=G\left[A\left(\frac{4J_1(h)}{h}-2J_0(h)\right)+B\left(\frac{4J_1(k)}{k}-2J_0(k)\right)\right.$$
$$\left.+C\left(2J_0(k)-\frac{4J_1(k)}{k}+kJ_1(k)\right)\right]\begin{Bmatrix}\cos\gamma z/a\\ \sin\gamma z/a\end{Bmatrix}\cos(\theta+\delta)\cos pt, \quad (8)$$

$$\tau_{rz}=G\left[A\left(\frac{2J_1(h)}{h}-2J_0(h)\right)+B\frac{\gamma^2-k^2}{\gamma^2}\left(\frac{J_1(k)}{k}-J_0(k)\right)-C\frac{J_1(k)}{k}\right]\begin{Bmatrix}-\sin\beta z/a\\ \cos\beta z/a\end{Bmatrix}\sin(\theta+\delta)\cos pt. \quad (9)$$

In order that all three boundary stresses be zero at the curved surface without (A), (B), and (C) being zero, the expressions in the three brackets must be zero. This requirement gives the three equations:*

$$B=A\frac{a_2c_1-a_1c_2}{b_1c_2-b_2c_1}, \tag{10}$$

$$C=A\frac{a_1b_2-a_2b_1}{b_1c_2-b_2c_1}, \tag{11}$$

$$\begin{vmatrix} a_1, & b_1, & c_1 \\ a_2, & b_2, & c_2 \\ a_3, & b_3, & c_3 \end{vmatrix}=0, \tag{12}$$

where

$$a_1=\frac{2J_1(h)}{h}-J_0(h)+\frac{\gamma^2-k^2}{2h}J_1(h),$$

$$a_2=\frac{4J_1(h)}{h}-2J_0(h),$$

$$a_3=\frac{2J_1(h)}{h}-2J_0(h),$$

$$b_1=\frac{2J_1(k)}{k}-J_0(k)-kJ_1(k),$$

$$b_2=\frac{4J_1(k)}{k}-2J_0(k),$$

$$b_3=\frac{\gamma^2-k^2}{\gamma^2}\left(\frac{J_1(k)}{k}-J_0(k)\right),$$

$$c_1=J_0(k)-\frac{2J_1(k)}{k},$$

$$c_2=2J_0(k)-\frac{4J_1(k)}{k}+kJ_1(k),$$

$$c_3=-\frac{J_1(k)}{k},$$

* Eq. (12) with some slight differences in notation was given in Appendix I of reference 1; ih', if' and $(\beta r/l)^2$ given there correspond, respectively, to $h/2$, $k/2$ and $(\gamma/2)^2$ given here for the larger of the two real values of γ^2; h, f, and $(\alpha r/l)^2$ given there correspond respectively to $h/2$, $k/2$, and $-(\gamma/2)^2$ given here for the smaller (usually negative) of the two real values of γ^2.

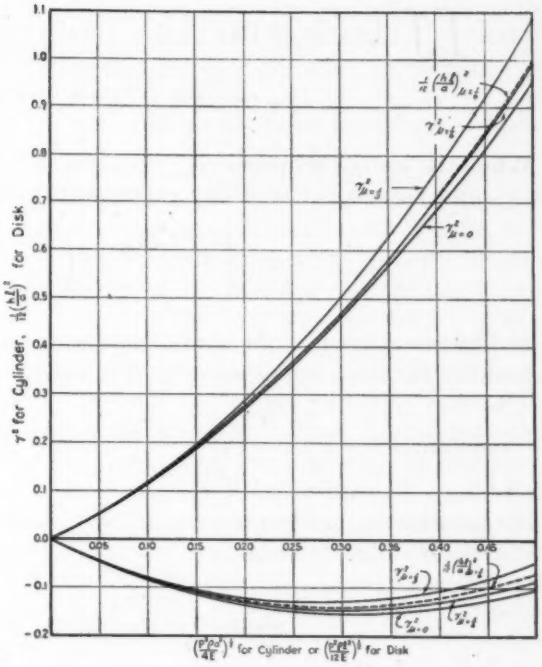

FIG. 1. Real roots of γ^2 in Eq. (12) *versus* $(p^2\rho a^2/4E)^{\frac{1}{2}}$ for $\mu=0$, 1/6 and 1/3, and 1/12 the real roots of $(hl/a)^2$ in Eq. (27) *versus* $(p^2\rho l^2/12E)^{\frac{1}{2}}$ for $\mu=1/6$.

$$h=\left[\frac{(1+\mu)(1-2\mu)}{1-\mu}\frac{p^2\rho a^2}{E}-\gamma^2\right]^{\frac{1}{2}},$$

$$k=\left[2(1+\mu)\frac{p^2\rho a^2}{E}-\gamma^2\right]^{\frac{1}{2}}.$$

Equation (12), giving the necessary relation between γ^2, μ, and $p^2\rho a^2/E$ in order that there be no boundary stresses at the curved surface, is a transcendental equation in γ^2 for given values of μ and $p^2\rho a^2/E$. This transcendental equation in γ^2 has one real root that is always positive and one real root that is negative for $p^2\rho a^2/E$ less than $3.386/(1+\mu)$. All of the other roots are complex. The present writer is of the opinion that a solution satisfying all the conditions exactly, those at the plane surfaces in addition to those at the curved surface, could be obtained from the use of all of these roots. But in this paper, only the two real roots are used since they are sufficient to meet the requirement that there be no resultant shear force and no resultant moment at the plane surfaces. Figure 1 shows these real roots *versus* $(p^2\rho a^2/4E)^{\frac{1}{2}}$ for $\mu=0$, $\frac{1}{6}$, and $\frac{1}{3}$.

The total shear force across a circular cross section is given by

$$\text{shear}=\int_0^a\int_0^{2\pi}[\tau_{rz}\sin(\theta+\delta)+\tau_{\theta z}\cos(\theta+\delta)]rdrd\theta, \quad (13)$$

and the moment on the section is given by

$$\text{moment}=\int_0^a\int_0^{2\pi}\sigma_z[r\sin(\theta+\delta)]rdrd\theta. \quad (14)$$

When the sum of solutions (A), (B), and (C) with $n=1$ and $\beta=\gamma$ is substituted into the expressions for τ_{rz} and $\tau_{\theta z}$ and the resulting expressions substituted into Eq. (13), the result after integration is

$$\text{shear}=G\pi a^2\gamma\left[A\frac{2J_1(h)}{h}+B\left(\frac{\gamma^2-k^2}{\gamma^2}\right)\frac{J_1(k)}{k}+C\frac{J_1(k)}{k}\right]\begin{Bmatrix}-\sin\gamma z/a\\ \cos\gamma z/a\end{Bmatrix}\cos pt. \quad (15)$$

In like manner when the sum of solutions (A), (B), and (C) is substituted into the expression for σ_z and the resulting expression substituted into Eq. (14), the result after integration is

$$\text{moment}=2G\pi a^3\left[A\frac{2h^2-k^2-\gamma^2}{2h^2}\left(\frac{2}{h}J_1(h)-J_0(h)\right)+B\left(\frac{2}{k}J_1(k)-J_0(k)\right)\right]\begin{Bmatrix}\cos\gamma z/a\\ \sin\gamma z/a\end{Bmatrix}\cos pt. \quad (16)$$

By substituting the expressions for the factors (B) and (C) given in Eqs. (10) and (11) into Eqs. (15) and (16) there is obtained

$$\text{shear}=\frac{G\pi a^2\gamma A}{c_5}[a_5c_5-b_4b_5-c_3c_4]\begin{Bmatrix}-\sin\gamma z/a\\ \cos\gamma z/a\end{Bmatrix}\cos pt, \quad (17)$$

and

$$\text{moment}=\frac{2G\pi a^3A}{c_5}[a_4c_5+c_1b_5]\begin{Bmatrix}\cos\gamma z/a\\ \sin\gamma z/a\end{Bmatrix}\cos pt, \quad (18)$$

where

$$a_4=\frac{2h^2-k^2-\gamma^2}{4h^2}a_2, \quad b_4=\left(\frac{\gamma^2-k^2}{\gamma^2}\right)\frac{J_1(k)}{k}, \quad c_4=a_1b_2-a_2b_1,$$

$$a_5=\frac{2J_1(h)}{h}, \quad b_5=a_1c_2-a_2c_1, \quad c_5=b_1c_2-b_2c_1.$$

Obviously, no one value of γ in Eqs. (17) and (18) will make both the shear and moment zero at the plane surfaces $z=\pm l/2$. The superposition of two solutions based on two different permissible values of γ is required. As mentioned previously, two such solutions based on the two real values of γ^2 that satisfy Eq. (12) will be used. To distinguish between the solutions, primes will be added to the factors characteristic of the solution for which γ^2 is always positive, thus γ', h', k', A', etc.* On the basis of this notation γ, h', and k' will be imaginary quantities whereas γ', h, and k will be real quantities. When the shear and moment are each set equal to zero at $z=\pm l/2$ for the sum of two such solutions, the following two equations are obtained (see Eqs. (17) and (18)):

$$G\pi a^2\left[\frac{A\gamma}{c_5}(a_5c_5-b_4b_5-c_3c_4)\begin{Bmatrix}-\sin\gamma l/2a\\ \cos\gamma l/2a\end{Bmatrix}+\frac{A'\gamma'}{c_5'}(a_5'c_5'-b_4'b_5'-c_3'c_4')\begin{Bmatrix}-\sin\gamma' l/2a\\ \cos\gamma' l/2a\end{Bmatrix}\right]\cos pt=0, \quad (19)$$

$$2G\pi a^3\left[\frac{A}{c_5}(a_4c_5+c_1b_5)\begin{Bmatrix}\cos\gamma l/2a\\ \sin\gamma l/2a\end{Bmatrix}+\frac{A'}{c_5'}(a_4'c_5'+c_1'b_5')\begin{Bmatrix}\cos\gamma' l/2a\\ \sin\gamma' l/2a\end{Bmatrix}\right]\cos pt=0. \quad (20)$$

Upon eliminating A and A' from these two equations there is obtained

$$\frac{a_4c_5+c_1b_5}{\gamma(a_5c_5-b_4b_5-c_3c_4)}\begin{Bmatrix}-\cot\gamma l/2a\\ \tan\gamma l/2a\end{Bmatrix}=\frac{a_4'c_5'+c_1'b_5'}{\gamma'(a_5'c_5'-b_4'b_5'-c_3'c_4')}\begin{Bmatrix}-\cot\gamma' l/2a\\ \tan\gamma' l/2a\end{Bmatrix}. \quad (21)$$

* h' then becomes the same as $2ih'$ in reference 1, k' the same as $2if'$, etc.

Eqs. (21) and (12) constitute the solution of the problem of flexural vibration of a cylinder. These equations give the necessary relations between the parameters μ, $p^2\rho a^2/E$, and l/a. In the limit as l/a becomes large:

$\gamma l/a$ approaches imG.
$\gamma' l/a$ approaches m.
Eq. (21) with the upper terms, reduces to the first factor of Eq. (5).
Eq. (21) with the lower terms, reduces to the second factor of Eq. (5).
Eq. (12) reduces to Eq. (1).

The most direct procedure for obtaining numerical values giving the relationship between μ, $p^2\rho a^2/E$, and l/a is as follows:

First, assume values of μ and $p^2\rho a^2/E$ and solve by trial for the two real values of γ^2 that satisfy Eq. (12). (Results for $\mu=0$, $\frac{1}{6}$ and $\frac{1}{3}$ are shown in Fig. 1.) The square roots of these values give γ, an imaginary quantity and γ', a real quantity.

Second, for these values of γ and γ' solve by trial for the various values of l/a that satisfy Eq. (21). When the upper terms in the braces are used, the values of l/a will be for the first, third, etc., modes of vibration and when the lower terms are used the values of l/a will be for the second, fourth, etc., modes.

The results of calculations can be put in the form

$$\frac{p^2\rho a^2}{E}=\frac{m^4}{4T}\left(\frac{a}{l}\right)^4, \tag{22}$$

where m is the m of Eqs. (1) and (5) and T is a factor which depends on μ and l/a and the mode of vibration. The results of the calculations are discussed in some detail in reference 1 and are shown graphically in Figs. 1 and 4 of reference 1. Fig. 1 of reference 1 shows T_1, the T for the first mode, *versus* $a/2l$ for three different values of μ. Figure 4 of reference 1 shows the ratios of the 2nd, 3rd, 4th, and 5th resonant frequencies to the first *versus* $a/2l$. In reference 1 it is shown that Goens' solution[11] of Timoshenko's differential equation (Eq. (3a)) is in good agreement with the equations given here if the shear constant K' is given the proper value. The proper value depends on Poisson's ratio, being about $\frac{5}{6}$ for $\mu=0$, $\frac{8}{9}$ for $\mu=\frac{1}{6}$ and 0.85 for $\mu=\frac{1}{3}$. If T is set equal to unity, then since $p=2\pi f$, Eq. (22) reduces to Eq. (1).

FLEXURAL VIBRATION OF A DISK (FLEXURAL VIBRATION AS A CIRCULAR PLATE)

As stated previously, the requirement of no boundary stresses at the plane surfaces can be met by the sum of solutions (A) and (B) if k in solution (B) is set equal to h in solution (A). For flexural vibration of a disk the lower terms in the braces are applicable but the upper ones are not.

When the sum of solutions (A) and (B) is substituted into the expressions for σ_z, τ_{rz}, and $\tau_{\theta z}$, the result—after setting k equal to h and $z=\pm l/2$ and using only the lower terms in the braces—is:

$$\sigma_z=2G\left[A\left(\frac{h^2-\beta^2}{2h}\right)\sin\frac{\gamma l}{2a}+Bh\sin\frac{\beta l}{2a}\right]J_n\left(\frac{hr}{a}\right)\sin(n\theta+\delta)\cos pt, \tag{23}$$

$$\tau_{rz}=2G\left[\frac{A\gamma}{h}\cos\frac{\gamma l}{2a}-B\frac{h^2-\beta^2}{2\beta h}\cos\frac{\beta l}{2a}\right]a\frac{\partial J_n\left(\frac{hr}{a}\right)}{\partial r}\sin(n\theta+\delta)\cos pt, \tag{24}$$

$$\tau_{\theta z}=2G\left[\frac{A\gamma}{h}\cos\frac{\gamma l}{2a}-B\frac{h^2-\beta^2}{2\beta h}\cos\frac{\beta l}{2a}\right]\frac{na}{r}J_n\left(\frac{hr}{a}\right)\cos(n\theta+\delta)\cos pt. \tag{25}$$

All three boundary stresses will be zero at the plane surfaces if the expressions in the brackets are zero. This requirement gives the following two equations:

[11] E. Goens, "Über die Bestimmung des Elastizitätsmoduls von Stäben mit Hilfe von Biegungsschwingungen," Ann. d. Physik [B] **11**, 649–678 (1931).

$$B=-\frac{h^2-\beta^2}{2h^2}\frac{\sin\dfrac{\gamma l}{2a}}{\sin\dfrac{\beta l}{2a}}A, \tag{26}$$

$$(h^2-\beta^2)^2\tan\frac{\gamma l}{2a}+4\beta\gamma h^2\tan\frac{\beta l}{2a}=0, \tag{27}$$

where

$$\gamma=\left[\frac{(1+\mu)(1-2\mu)}{1-\mu}\frac{p^2\rho a^2}{E}-h^2\right]^{\frac{1}{2}},$$

$$\beta=\left[2(1+\mu)\frac{p^2\rho a^2}{E}-h^2\right]^{\frac{1}{2}}.$$

For given values of μ and $p^2\rho l^2/E$ Eq. (27) is a transcendental equation in $(hl/a)^2$ with two real roots. These two roots, divided by 12, *versus* $(p^2\rho l^2/12E)^{\frac{1}{2}}$ for $\mu=\frac{1}{6}$ are shown in Fig. 1 along with values of γ^2 in Eq. (12) *versus* $(p^2\rho a^2/4E)^{\frac{1}{2}}$. These scales for ordinates and abscissas put both sets of roots on approximately the same basis. As shown in Fig. 1 corresponding curves for $\frac{1}{12}(hl/a)^2$ are almost identical to those for γ^2. In addition to the similarity just noted, much of the following development for the disk is similar to that for the cylinder; compare the following pairs of equations: (13) and (28), (14) and (29), (15) and (30), (16) and (31), (17) and (32), (18) and (33), (21) and (37).

The transverse force across any element, l by a $d\theta$, of the curved surface is given by*,[12]

$$\text{transverse force}=ad\theta\int_{-l/2}^{l/2}\left(\tau_{rz}+\frac{1}{a}\frac{\partial}{\partial\theta}\tau_{r\theta z}\right)dz, \tag{28}$$

and the moment on the same element is given by

$$\text{moment}=ad\theta\int_{-l/2}^{l/2}z\sigma_r dz, \tag{29}$$

where each expression is evaluated for $r=a$.

When the sum of solutions (A) and (B) with $r=a$ and $k=h$, (only the lower terms in the braces being used) is substituted into the expressions for τ_{rz}, $\tau_{r\theta}$, and σ_r and the resulting expressions substituted into Eqs. (28) and (29), the following equations are obtained after integration.

$$\text{Transverse force}=4Ga^2d\theta\sin(n\theta+\delta)\cos pt\left\{\left[A\sin\frac{\gamma l}{2a}+B\frac{\beta^2-h^2}{2\beta^2}\sin\frac{\beta l}{2a}\right]\frac{\partial}{\partial h}J_n(h)\right.$$
$$\left.-\left[\frac{An^2}{\gamma^2}\left(1-\frac{\gamma l}{2a}\cot\frac{\gamma l}{2a}\right)\sin\frac{\gamma l}{2a}+\frac{Bn^2}{\beta^2}\left(1-\frac{\beta l}{2a}\cot\frac{\gamma l}{2a}\right)\right]\left[\frac{\partial J_n(h)}{\partial h}-\frac{J_n(h)}{h}\right]\right\}, \tag{30}$$

$$\text{moment}=4Ga^3hd\theta\left[\frac{A}{\gamma^2}\left(\frac{2\gamma^2+h^2-\beta^2}{2h^2}J_n(h)+\frac{\partial^2}{\partial h^2}J_n(h)\right)\left(1-\frac{\gamma l}{2a}\cot\frac{\gamma l}{2a}\right)\sin\frac{\gamma l}{2a}\right.$$
$$\left.+\frac{B}{\beta^2}\frac{\partial^2}{\partial h^2}J_n(h)\left(1-\frac{\beta l}{2a}\cot\frac{\beta l}{2a}\right)\sin\frac{\beta l}{2a}\right]\sin(n\theta+\delta)\cos pt. \tag{31}$$

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* The Kirchhoff boundary conditions for a free boundary are used here.

[12] S. Timoshenko, *Theory of Plates and Shells* (McGraw-Hill Book Company, Inc., New York, 1940), pp. 89–99.

From Eqs. (26), (30), and (31):

$$\text{transverse force} = 4Ga^3 d\theta A \sin\frac{\gamma l}{2a}\phi_1(h,\gamma,\beta)\sin(n\theta+\delta)\cos pt, \tag{32}$$

$$\text{moment} = 4Ga^3 d\theta A \sin\frac{\gamma l}{2a}F_1(h,\gamma,\beta)\sin(n\theta+\delta)\cos pt, \tag{33}$$

where

$$\phi_1(h,\gamma,\beta)=\frac{(h^2+\beta^2)^2}{4h^2\beta^2}\frac{\partial J_n(h)}{\partial h}-n^2\left[\frac{1-\frac{\gamma l}{2a}\cot\frac{\gamma l}{2a}}{\gamma^2}+\frac{\beta^2-h^2}{2h^2\beta^2}\left(1-\frac{\beta l}{2a}\cot\frac{\beta l}{2a}\right)\right]\left[\frac{\partial J_n(h)}{\partial h}-\frac{J_n(h)}{h}\right],$$

$$F_1(h,\gamma,\beta)=\frac{h}{\gamma^2}\left[\left(\frac{2\gamma^2+h^2-\beta^2}{2h^2}J_n(h)+\frac{\partial^2}{\partial h^2}J_n(h)\right)\left(1-\frac{\gamma h}{2a}\cot\frac{\gamma l}{2a}\right)\right.$$

$$\left.-\frac{(h^2-\beta^2)\gamma^2}{2\beta^2h^2}\frac{\partial^2}{\partial h^2}J_n(h)\left(1-\frac{\beta l}{2a}\cot\frac{\beta l}{2a}\right)\right].$$

No one value of hl/a in Eqs. (32) and (33) will make both the transverse force and the moment zero. The superposition of two solutions based on two different permissible values of hl/a is required. Two solutions based on the two real values of $(hl/a)^2$ that satisfy Eq. (27) will be used. To distinguish between these solutions primes will be added to the factors characteristic of the solutions for which h^2 is usually negative, thus h', γ', β', A', B'. With this notation h', usually, and γ and β always, will be imaginary quantities and h, always, and γ' and β' usually will be real quantities.

When the transverse force and the moment are set equal to zero for the sum of two such solutions, the following equations are obtained:

$$A\sin\frac{\gamma l}{2a}\phi_1(h,\gamma,\beta)+A'\sin\frac{\gamma' l}{2a}\phi_1(h',\gamma',\beta')=0, \tag{34}$$

$$A\sin\frac{\gamma l}{2a}F_1(h,\gamma,\beta)+A'\sin\frac{\gamma' l}{2a}F_1(h',\gamma',\beta')=0. \tag{35}$$

Upon eliminating A and A' from these two equations there is obtained:

$$\phi_1(h,\gamma,\beta)F_1(h',\gamma',\beta')=\phi_1(h',\gamma',\beta')F_1(h,\gamma,\beta). \tag{36}$$

Equation (36) can be written in the form

$$\frac{\gamma}{\gamma'}\phi_2(h,\gamma,\beta)F_2(h',\gamma',\beta')=F_2(h,\gamma,\beta)\phi_2(h',\gamma',\beta'), \tag{37}$$

where

$$\phi_2(h,\gamma,\beta)=h^3\frac{\partial}{\partial h}J_n(h)+C_1(1-\mu)n^2\left[h\frac{\partial}{\partial h}J_n(h)-J_n(h)\right],$$

$$F_2(h,\gamma,\beta)=C_2h^2J_n(h)+C_3(1-\mu)\left[h\frac{\partial}{\partial h}J_n(h)-n^2J_n(h)\right],$$

$$C_1=-\frac{4h^2\beta^2}{(1-\mu)(h^2+\beta^2)^2}\left[\frac{1-\frac{\gamma l}{2a}\cot\frac{\gamma l}{2a}}{\gamma^2}+\frac{\beta^2-h^2}{2h^2}\frac{1-\frac{\beta l}{2a}\cot\frac{\beta l}{2a}}{\beta^2}\right],$$

$$C_2=-\frac{i4h^2\beta^2}{(h^2+\beta^2)^2}\left[\frac{2\gamma^2-h^2-\beta^2}{2h\gamma}\left(1-\frac{\gamma l}{2a}\cot\frac{\gamma l}{2a}\right)-\frac{(\beta^2-h^2)\gamma}{2\beta^2 h}\left(1-\frac{\beta l}{2a}\cot\frac{\beta l}{2a}\right)\right],$$

$$C_3=\frac{i4h^2\beta^2}{(1-\mu)(h^2+\beta^2)^2}\left[\frac{h}{\gamma}\left(1-\frac{\gamma l}{2a}\cot\frac{\gamma l}{2a}\right)+\frac{(\beta^2-h^2)\gamma}{2\beta^2 h}\left(1-\frac{\beta l}{2a}\cot\frac{\beta l}{2a}\right)\right].$$

Equations (37) and (27) constitute the solution of the problem of flexural vibration of a disk. In the limit as a/l becomes large:

h reduces to M.
h' reduces to iM.
Eq. (27) reduces to Eq. (2).
C_1, C_2, C_3, C_1', $(\gamma/\gamma')C_2'$, and $(\gamma/\gamma')C_3'$ all reduce to unity.
Consequently,
Eq. (37) reduces to Eq. (6).

Equations (37) and (27) are very similar to Eqs. (21) and (12) and the procedure for obtaining numerical values giving the relationship between μ, $p^2\rho l^2/E$ and a/l from Eqs. (36) and (27) is very similar to that previously recommended for obtaining numerical values giving the relationship between μ, $p^2\rho a^2/E$ and l/a from Eqs. (21) and (12). The chief difference lies in the fact that the disk, vibrating as a plate, may have both nodal diameters and nodal circles whereas a cylinder, vibrating as a rod, may have only nodal diameters. The recommended procedure is as follows:

First, assume values of μ and $p^2\rho l^2/12E$ and solve by trial for the two real values of $(hl/a)^2$ that satisfy Eq. (27). (Results for $\mu=\frac{1}{6}$ are shown in Fig. 1.)* The square roots of these quantities give hl/a a real quantity and $h'l/a$ usually an imaginary quantity.

Second, for these values of μ and $p^2\rho l^2/12E$ compute values of C_1, C_2, C_3, C_1', $(\gamma/\gamma')C_2'$, and $(\gamma/\gamma')C_3'$. (Results for $\mu=\frac{1}{6}$ are shown in Fig. 2.)

Third, select a value of n, the number of nodal diameters for the modes of vibration for which the investigation is to be made.

Fourth, after substituting assumed and computed values in Eq. (37), solve by trial for the various values of a/l that satisfy the equation. If n is zero or unity, the lowest value of a/l will be for one nodal circle, the next for two nodal circles, etc. If n is two or a larger number, the lowest value of a/l will be for vibration without a nodal circle, the next for one nodal circle, etc.

The results of the calculations can be put in the form

$$9(1-\mu^2)\frac{p^2\rho l^2}{12E}=\frac{M^4}{T}\left(\frac{l}{2a}\right)^4, \qquad (38)$$

where T, similar to the T of Eq. (22), is a factor that depends on μ, a/l and the mode of vibration. Figure 3 shows T_{20} (the T for two nodal diameters and one nodal circle) and T_{01} (the T for no nodal diameter and one nodal circle) *versus* $l/2a$ for $\mu=\frac{1}{6}$. Also shown is T_1 for $\mu=\frac{1}{6}$ for the first mode of flexural vibration of a cylinder *versus* $2a/l$. The curves for T_{01} and for T_1 in Fig. 3 are almost identical.

For purposes of determining E from resonant frequencies it is convenient to write Eqs. (22) and (38) in the forms:

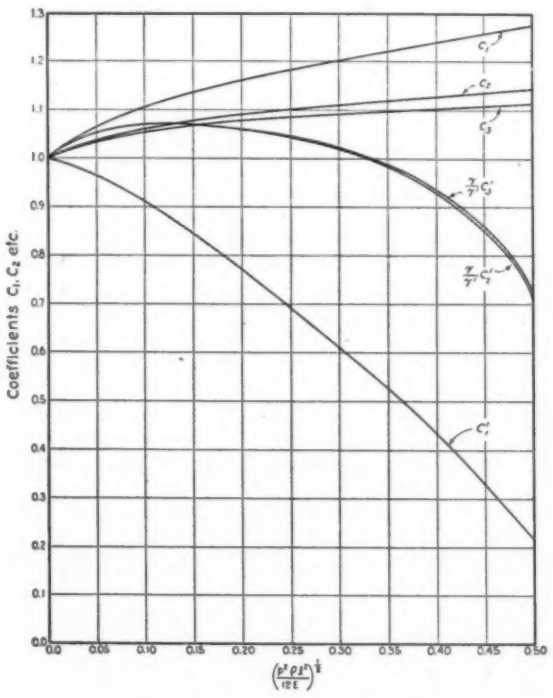

FIG. 2. Coefficients C_1, C_2, etc. in Eq. (37) *versus* $(p^2\rho l^2/12E)^{\frac{1}{2}}$ for $\mu=1/6$.

* The value $\frac{1}{6}$ for μ was selected for this and the subsequent computations because it is fairly representative of μ for concrete and the computations were made primarily to provide formulas for the evaluation of Young's modulus from experimentally determined resonant frequencies of concrete specimens in the form of disks.

$$E=\frac{16\pi l^3 W f^2}{g a^4 m^4}T, \qquad (22a)$$

$$E=\frac{48\pi(1-\mu^2)a^2 W f^2}{g l^3 M^4}T, \qquad (38a)$$

where W = weight of specimen and g = acceleration of gravity.

Example 1:

Cylinder 6 in. diam., 12 in. length, weight 29.4 lb., frequency of first mode 4000 cycles per second.

μ assumed to be $\frac{1}{6}$, $T_1=2.10$ from Fig. 3. Therefore,

$$E=\frac{16\pi 12^3\times 29.4\times 4000^2}{386\times 3^4\times 4.730^4}2.10=5.48\times 10^6 \text{ lb./in.}^2$$

Example 2:

Disk 6-in. diameter, 2-in. thick, weight 4.9 lb., lowest frequency (2 nodal diameters and no nodal circle) 7000 cycles per second. μ assumed to be $\frac{1}{6}$, $M_{20}=2.398$ by interpolation from table in text, $T_{20}=1.36$ from Fig. 3.

$$E=\frac{48\pi(1-.0278)\times 3^2\times 4.9\times 7000^2}{386\times 2^3\times 2.398^4}1.36$$

$$=4.22\times 10^6 \text{ lb./sq. in.}$$

DISCUSSION

The above analysis has, by means of the differential equations of the theory of elasticity, given solutions to two problems in flexural vibration of unrestrained bodies, that of flexural vibration of a cylinder and that of flexural vibration of a disk. Certain simplifying assumptions in regard to boundary conditions were made in the analysis and therefore the resulting solutions are not of unlimited application. A review of these simplifying assumptions follows:

In regard to the cylinder the requirements for the curved boundary were satisfied exactly but those for the plane ends were only approximately satisfied. Instead of meeting the requirement of no boundary stress at the plane ends, the resultant transverse force and the resultan moment at each end was made zero.

In regard to the disk the requirements for the plane surfaces were met exactly, but those for the curved surface were only approximately satisfied. Instead of meeting the requirement of no boundary stress at the curved surface, the simplified Kirchhoff boundary conditions for a free surface we : met.

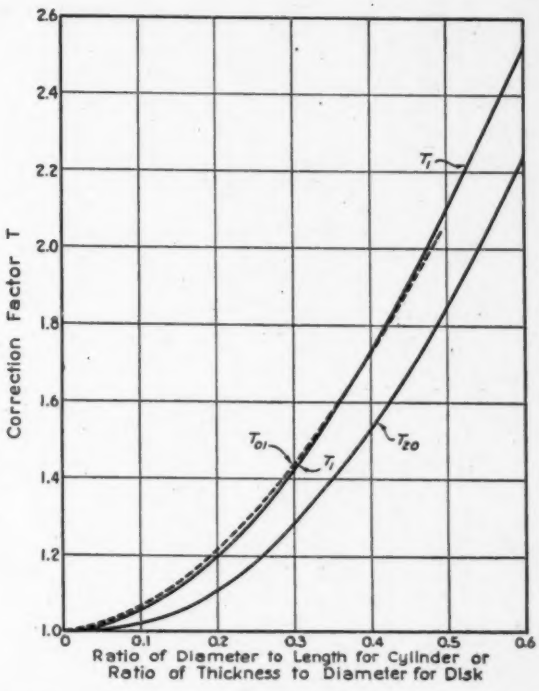

FIG. 3. The factor T_1 for cylinder and the factors T_{20} and T_{01} for disk *versus* ratios of dimensions.

Just how much the solutions are limited by the introduction of the simplifying assumptions has not been adequately investigated, but it is believed that these simplifications introduce very little error in the solution for the cylinder for diameter-to-length ratios up to unity for the mode of lowest frequency and very little error in the solution for the disk for thickness-to-diameter ratios up to one-half for the modes of the two lowest frequencies. The solutions would be limited to smaller ratios of the dimensions for modes of higher frequencies.

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High Dispersion Electron Diffraction by Primary Magnification

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A method for attaining high dispersion in electron diffraction is presented. High dispersion may be obtained by primary magnification of a diffraction pattern formed in the normal manner at the object plane of a magnetic or electrostatic lens. Dispersion may be varied continuously by changing the lens current or voltage. The design of diffraction cameras of this type is discussed and their value in diffraction problems pointed out. The validity of the method is established by diffraction patterns obtained using a modified electron microscope adapter.

ELECTRON diffraction has proved sufficiently unique and successful during the past decade for determining the crystalline structure of thin films and the molecular structure of vapors to be accepted as a physical tool in industrial laboratories. It has often been limited in application, however, by its inherently low dispersion for high values of lattice spacings.

In the case of both x-ray and electron diffraction, difficulty is experienced in long spacing measurements since the portion of the diffraction pattern corresponding to these spacings occurs at small angles with the undiffracted beam. In x-ray diffraction this difficulty can be obviated only through use of long specimen-plate distances and masking of the undiffracted beam.[1,2] Although similar methods may be employed in the case of electron diffraction, certain practical experimental difficulties are encountered.

It is the purpose of this paper to present a new principle and design of electron diffraction systems whereby very high dispersion may be attained and the usefulness of electron diffraction studies consequently extended. Briefly, it will be shown that this can be accomplished by primary magnification[3] of a focused electron diffraction image using either a magnetic or an electrostatic lens. The degree of dispersion may thus be varied continuously, through changes of lens current or voltage, and is limited essentially only by the resolution of the original pattern.

DISPERSION

An electron diffraction camera can be considered analogous to an optical grating spectrograph. In the latter, a homogeneous grating of single spacing is illuminated with polychromatic light in order to reveal by diffraction the wave-lengths comprising the incident light; in the electron diffraction camera, however, a beam of electrons of single wave-length is directed onto a multi-spacing crystal grating to produce a diffraction pattern from which all of the periodic spacings of the crystal may be calculated. It is, therefore, evident that the two factors governing the design of an optical spectrograph—high resolving power and sufficient dispersion for its full utilization—are also important in the design of an electron diffraction camera. The resolving power of an electron diffraction system is principally determined by properties of the crystal grating such as the perfection and limited extent of the crystal, absorption, refraction and multiple scattering. Since the crystal grating is the object of study and will necessarily vary widely both in its physical and chemical properties, these grating factors usually cannot be controlled. Instrumental variables, however, which can be controlled by proper design are the homogeneity of the electron beam, the beam size and the aberration of the lenses employed. With proper design, such systems may have rather high resolving power. Unfortunately in the diffraction systems normally used, the analog of optical dispersion is so low at larger values of crystal lattice spacings that full utilization of the resolving power is not made.

The linear dispersion of an electron diffraction system may be defined as the linear change measured on the photographic plate produced by a variation in lattice spacing of the diffracting crystal. This quantity may be shown to be proportional to $n\lambda R/d^2$, where n is the order of diffraction, λ is the electron wave-length, R is the specimen-plate distance, and d is the interplanar spacing.[4] In further analogy with optical spectro-

[1] R. S. Bear, J. Am. Chem. Soc. 66, 1297 (1944).
[2] I. Fankuchen and M. Schneider, J. Am. Chem. Soc. 66, 500 (1944).
[3] The expression "primary magnification" refers to magnification of the diffraction pattern before the electrons strike the photographic plate.

[4] An expression for linear dispersion may be derived as follows:
The inherently small angles of diffraction, θ, permit

graphs, the linear dispersion is proportional to the magnification of the image, provided that the dispersing element is kept constant.

The rapid decrease in dispersion with increase in the distance between diffracting planes sets the usable upper limit of lattice spacings with present diffraction systems at about 5A. Although sufficient for the study of most inorganic materials, such a 5A limit is entirely inadequate for the majority of organic crystals where planar spacings of 10–30A frequently occur. A need was felt, therefore, for increasing the dispersion. A theoretical upper limit of detectable spacings exists because the low penetration of electrons into matter results in a serious reduction of the number of contributing planes for reflection at large spacings. The limit will be dependent upon the degree of crystallinity and the structure and composition of the material, for these are the factors which determine the scattering power or intensity of reflection by a given atomic plane. The effect, as observations are made at progressively longer spacings, will be first the absence of an increasing number of diffraction maxima from weakly reflecting planes and finally the absence of maxima even from strongly reflecting planes. Fortunately, in many instances, measurement of only the stronger reflections near the theoretical limit would be of great value.

With low dispersion systems difficulties are also encountered in the analysis of complex mixtures or of structurally similar materials, and in solid solubility measurements where very accurate line spacing determinations are required. Not only is the measurement of longer spacings inaccurate, but often the resolution of closely lying reflections is difficult because of the finite line width and broadening of the recorded reflections by scattering within the photographic emulsion. High background intensity and halation about the center undiffracted beam both serve to mask to a very large extent the long spacing region. Primary electronic magnification would minimize these effects.

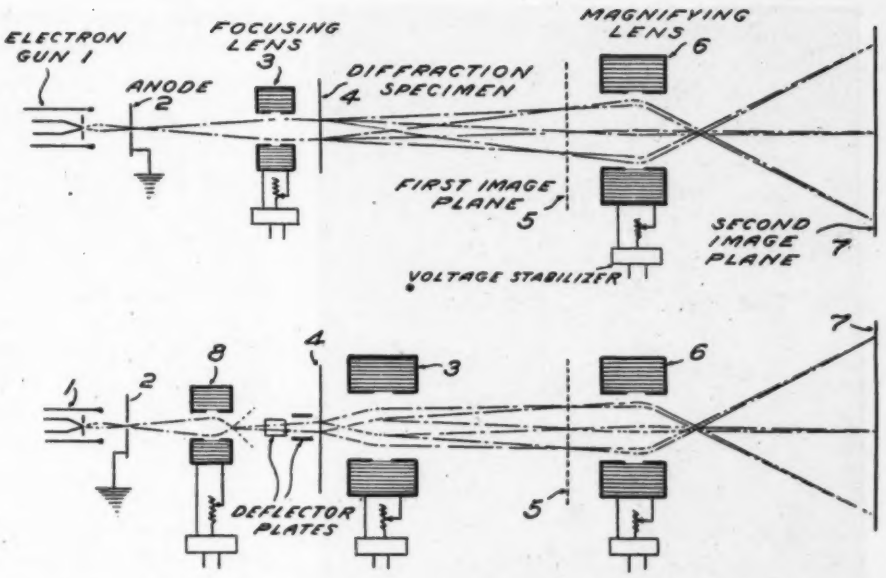

FIG. 1. Electron optics for two forms of the high dispersion electron diffraction system using magnetic lenses.

Although it has not yet been possible to investigate the various characteristics of the present system fully, the following is presented because of its interest to other designers of electron diffraction cameras, and to users of diffraction adapters[5] for electron microscopes.

INCREASE IN DISPERSION BY PRIMARY MAGNIFICATION

In the normal diffraction system, a collimated or focused beam of electrons is allowed to fall upon a specimen and the diffracted beams diverge at fixed angles to the undeviated beam over a definite specimen to photographic plate distance. For such a system, the dispersion may be varied merely by changing the wave-length of the incident electrons. Increasing the wave-length of the electrons by decreasing the voltage from 60 kv to 30 kv corresponds, however, to pattern magnification of only 1.4×.

The method of attaining high dispersion herein

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sin θ to be taken numerically equal to tan θ and to θ. In diffraction cameras based on simple rectilinear expansion of the diffraction pattern, $\theta = r/2R$ where r is the distance measured on the photographic plate from the undiffracted beam position to the position of diffraction. From Bragg's law, $\theta = n\lambda/2d$. Accordingly, $r = n\lambda R/d$ from which the *linear dispersion*, $\partial r/\partial d = -n\lambda R/d^2$, is obtained. The negative sign indicates the inverse relationship between r and d or the negative slope of $r-d$ curves.

[5] J. Hillier, R. Baker, and V. Zworykin, J. App. Phys. 13, 571 (1942).

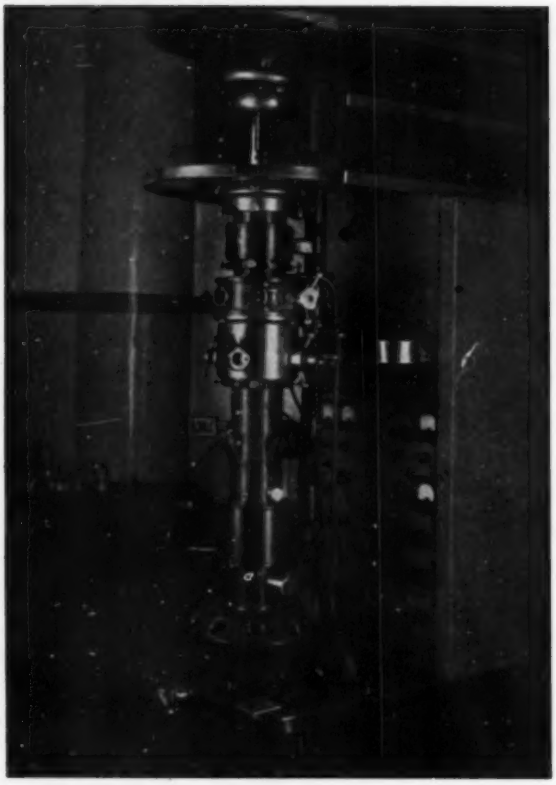

FIG. 2. RCA Type EMB electron microscope arranged for high dispersion electron diffraction.

presented and which achieves magnification through the use of a lens, is illustrated in two forms in Fig. 1. A beam of electrons is focused by focusing lens *3*, placed in either of two positions as shown, to a plane *5* intermediate between the specimen, *4*, and photographic plate *7*. This image plane then serves as the object plane of a magnifying lens *6* which forms a magnified image of the diffraction pattern on the photographic plate. The total magnification is determined by the object position of lens *6* and the current through the lens. A collimated rather than a focused beam may be used. The diffraction line width obviously increases as a result of magnification and, consequently, the initial beam width must be made small to retain adequate resolution. Reduction of beam size by apertures will in general be unsatisfactory because of the simultaneous reduction of intensity. Consequently, the use of a probe lens, *8* (lower drawing of Fig. 1) may be preferred. Such a probe lens permits reduction of the beam size over a rather wide range and intensity losses occasioned by the lens may be compensated by the use of a relatively large gun aperture. A more detailed discussion of a desirable lens system is given below.

a. Probe Lens

The anode aperture, *2*, serves as the initial object point of the lens system. Since it is desirable that the final image of aperture *2* be about 0.1 mm in diameter, the probe lens, *8*, must therefore be capable of reduced magnification equal to the product of the magnification of lenses *3* and *6*, and the ratio of aperture *2* to 0.1 mm. Aberration errors are not considered important in the probe lens as the object is axially located and small with respect to the lens aperture and the cross-sectional form of the electron beam is not of great importance. In spite of the fact that there is a loss in intensity at high reductions because of the strongly divergent character of the electron beam beyond the image point, it is possible with proper choice of gun aperture and total magnification, to obtain sufficient intensity for all practical conditions of operation.

b. Focusing Lens

The focusing lens is a low power lens which may be placed either before or after the specimen as indicated in the upper and lower parts, respectively, of Fig. 1. It is the lens commonly used in focusing type diffraction cameras. The position before the specimen may be preferable since aberration corrections would then be of less importance.

c. Magnifying Lens

The magnifying lens must be a corrected lens, and should allow as large a portion of the diffraction pattern to pass through as is required to cover the photographic plate. Two factors determine the total pattern magnification, the lens magnification and the size of the original diffraction pattern in the object plane of the lens. The size of the diffraction pattern to be magnified depends upon the distance of the object plane of the magnifying lens from the specimen. A small pattern size at the object plane permits a greater portion to be magnified, but a greater lens magnification is then required and consequently a smaller lens aperture is necessary to maintain spherical aberration at a minimum. An optimum position of the magnifying lens can be found where a useful total magnification range greater than 10× may be obtained. Diffraction patterns may be taken in the normal manner by operating with the magnifying lens shut off and with the pole piece removed, and by focusing directly on the photographic plate with the focusing lens.

Aberration errors are of importance inasmuch as the angular position and separation of the diffraction maxima must be faithfully reproduced. The principal errors encountered are spherical and chromatic aberrations, although coma and astigmatism assume importance for points at relatively large distances from the axis. Other aberrations which may occur such as "pin-cushion distortion" or non-planar focal field can be very greatly minimized by proper lens design, the use of lens apertures, stabilization of lens voltage, and provision for proper alignment of the lens system. Finally, the lens should be made with two equivalent, oppositely wound, coils[6] to neutralize image rotation. Rotation may otherwise not be equivalent at the outer and inner portions of an image and lead to errors in angular measurements of diffraction reflections.

EXPERIMENTAL VERIFICATION

In order to demonstrate the practicability of the above ideas, a series of experiments were performed using the diffraction adapter for the electron microscope which contains the various elements necessary for forming a high-dispersion diffraction system. Figure 2 illustrates the use of the RCA Type EMB electron microscope for high dispersion. The projector lens, containing the diffraction holder, and the objective lens are interchanged—the former to serve as the focusing lens and the latter (with pole piece removed) as the magnifying lens. The RCA Type EMU microscope may be similarly modified. If only transmission patterns are desired, the mount normally employed for microscopic specimens may be used in place of the diffraction holder and lens interchange is unnecessary. Although the geometrical relationship of the lenses is not ideal for this purpose, such a modified arrangement served to establish experimentally the present method of attaining high dispersion and to point out the possibility of modifying the RCA electron microscope for this purpose.

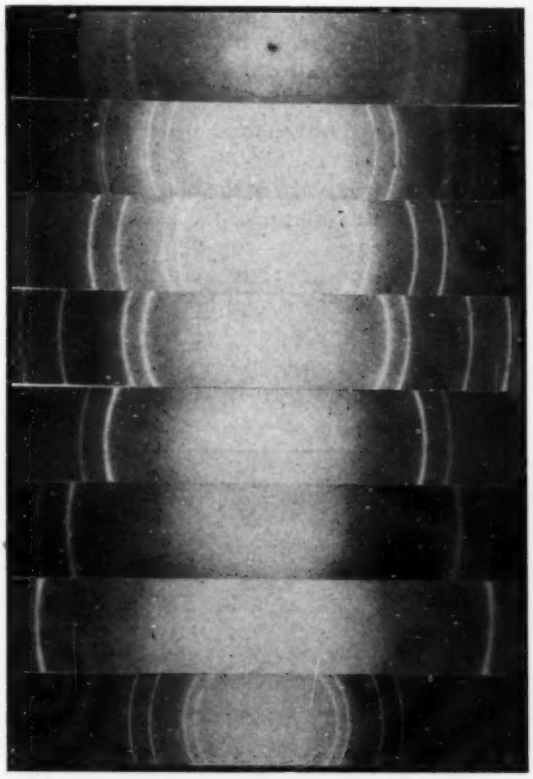

FIG. 3. Diffraction patterns of aluminum at various dispersions. 50 kv.

1. No magnification; 2. Magnification 0.43×;
3. Magnification 0.62×; 4. Magnification 0.86×;
5. Magnification 1.1×; 6. Magnification 1.4×;
7. Magnification 1.6×; 8. Normal.

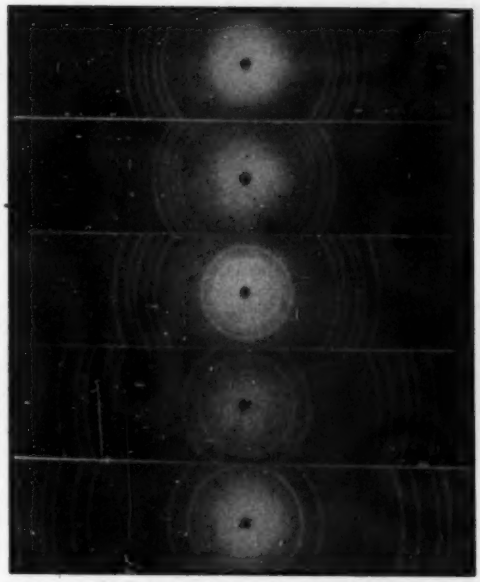

FIG. 4. Diffraction patterns of copper phthalocyanine at various dispersions. 50 kv.

1. No magnification; 2. Magnification 0.77×;
3. Magnification 1.1×; 4. Magnification 1.6×;
5. Magnification 1.9×.

Transmission diffraction patterns were obtained by first setting the specimen normal to the electron beam in the customary manner. A predetermined current, corresponding to the desired magnification, was passed through the magnifying lens. Finally, the current through the focusing lens was adjusted until its image plane coincided with the object plane of the magnifying lens. Coincidence occurred when maximum

[6] L. M. Myers, *Electron Optics* (D. Van Nostrand Company, Inc., New York, 1940), p. 207.

FIG. 5. Diffraction pattern of melamine at a primary magnification of 1.4×. Effective camera length—76.6 cm. 50 kv.

FIG. 6. Diffraction pattern of sulfadiazine at a primary magnification of 2.6×. Effective camera length—141 cm. 60 kv.

sharpness of the diffraction lines was observed on the viewing screen. Reflection patterns were taken in a similar manner except that it was usually necessary to readjust the specimen position after the final lens settings had been made.

Figure 3 shows a series of diffraction patterns of aluminum taken by transmission at various degrees of primary magnification. Figure 3–1 was taken with no current in the magnifying lens and in view of the long specimen to plate distance, the magnification is about 1.9× that obtained with the diffraction adapter in its normal position, Fig. 3–8. With small magnifying lens current, lower dispersion patterns are obtained, Figs. 3–2 to 3–4, because the initial crossing of electron trajectories is at small angles—indicated in Fig. 1. Further increase in lens current increases the crossing angle and consequently the total magnification increases beyond that of simple rectilinear expansion, as illustrated by Figs. 3–5 to 3–7. At still greater magnification, the inner (111) line was outside the area of the photographic plate. This series of photographs which represents an effective range of specimens to photographic plate distance without magnification of 23 to 86 cm and which was obtained on an instrument with a fixed distance of 54 cm, demonstrates clearly the manner in which the dispersion of a given instrument can be controlled.

Figure 4[7] shows a series of diffraction patterns of copper phthalocyanine at total magnification of 0.77× to 1.9×. Two inner lines whose spacings are 12.7A and 9.7A, respectively, are hidden by halation of the center spot in the first photograph but are brought out and are readily measureable at the higher dispersion of Fig. 4–4, thus illustrating the value of high dispersion for the study of long spacing reflections.

Figures 5[7] and 6[7] are diffraction patterns of typical organic materials taken using the present method, and represent an effective specimen to plate distance of 77 and 141 cm, respectively, obtained from a camera having a specimen to plate distance of 54 cm. The inner ring measurement in Fig. 5 is 4.96A and in Fig. 6 is 6.70A.

Figure 7 shows the diffraction patterns obtained by reflection from an oxidized surface of Armco iron at magnifications of 1.3× and 1.7×, respectively. A slight degree of preferred orientation and coarse grain structure is evident.

Note added in proof: After being submitted for publication, this manuscript was sent to Mr. Perry C. Smith of the Camden Laboratories of RCA. He informs us that some similar work is being pursued in their own laboratories.

[7] The diffraction lines have been retouched as there was insufficient contrast between the lines and the background of the original photographs to permit reproduction in printing.

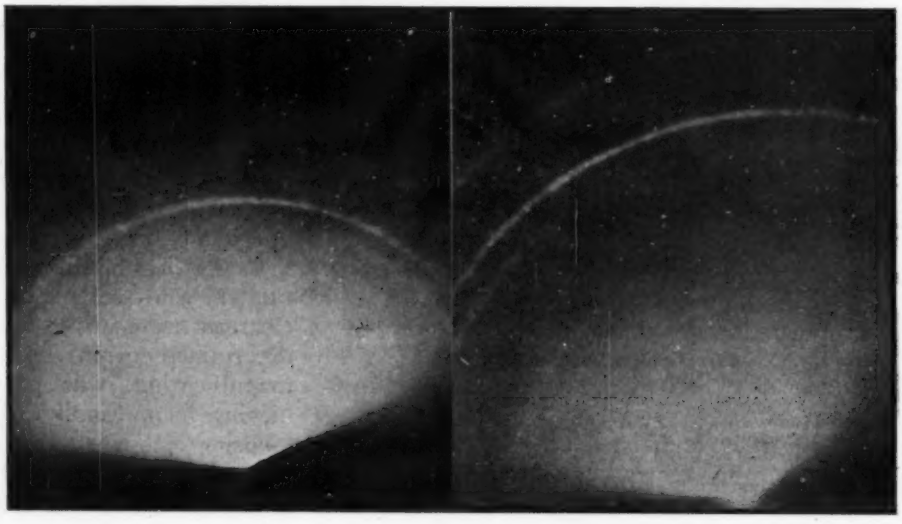

FIG. 7. Diffraction patterns of iron oxide (α-Fe_2O_3) taken by reflection at high dispersion. 60 kv. Left, magnification of 1.3×; Right, magnification of 1.7×.

Strain Hardening Under Combined Stresses*

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Experimental investigations of the strain hardening of metals under combined stresses are usually conducted so that the directions of the principal stresses as well as the ratios of their magnitudes remain constant during any one test. The paper is concerned with incompressible isotropic materials which are stressed in this manner and deform in accordance with certain postulates. The most general stress-strain relation which can arise under these circumstances is established, and some special cases of this relation are discussed.

1. INTRODUCTION

SUBJECTING thin-walled tubes to combined axial tension and internal pressure or torsion constitutes a frequently used means of investigating the plastic behavior of metals in the strain-hardening range.[1] In the case of combined axial tension and internal pressure the ratio of the axial load to the internal pressure is usually kept constant throughout any one test, and similarly in the case of combined tension and torsion the ratio of axial load and torque is kept constant. During such a test the directions of the principal stresses as well as the ratios of their magnitudes are preserved. For an isotropic material which is tested in this manner, the principal axes of stress and strain are bound to coincide. If the material is incompressible in addition to being isotropic, the ratios of the principal strains may be expected to remain constant during each test.[2] Moreover, if the material has identical stress-strain diagrams in pure tension and in pure compression, reversal of the signs of all stresses may generally be expected to lead to a mere reversal of the signs of all strains. Since, finally, a state of hydrostatic pressure cannot produce any deformation in an incompressible isotropic material, two states of stress which differ only by a state of hydrostatic pressure may be expected to produce identical deformations. This paper is concerned with incompressible isotropic materials which deform in accordance with the preceding postulates when tested in the manner defined above. The most general stress-strain relation which can arise under these circumstances is established, and some special cases of this relation are discussed.

2. THE GENERAL STRESS-STRAIN RELATION

In the following, the principal stresses will be denoted by σ_1, σ_2, σ_3, the principal strains by e_1, e_2, e_3. For the moderate deformations to which the following discussion is restricted, the incompressibility of the material is expressed by the equation

$$e_1+e_2+e_3=0. \tag{1}$$

If σ denotes the *mean normal stress*,

$$\sigma=\tfrac{1}{3}(\sigma_1+\sigma_2+\sigma_3), \tag{2}$$

the *stress deviation* is defined as a tensor which has the same principal axes as the given stress, but the principal values

$$s_1=\sigma_1-\sigma, \quad s_2=\sigma_2-\sigma, \quad s_3=\sigma_3-\sigma. \tag{3}$$

It follows from (2) and (3), that

$$s_1+s_2+s_3=0. \tag{4}$$

Two states of stress which differ only by a state of hydrostatic pressure, obviously have identical stress deviations. The postulate that two such states of stress produce identical deformations can therefore be fulfilled by letting the strain depend on the stress deviation rather than on the stress itself.

For *simple tension* or *compression* in the direction of the first principal axis, $\sigma_2=\sigma_3=0$, $\sigma=\sigma_1/3$, and hence

$$s_1=2\sigma_1/3, \quad s_2=s_3=-\sigma_1/3=-s_1/2. \tag{5}$$

Moreover, since the material is assumed to be incompressible and isotropic

$$e_2=e_3=-e_1/2. \tag{6}$$

As is seen from (5) and (6), stress and strain are completely determined, in this case, by the first

* This paper was presented at the Annual Meeting of the Society of Rheology, New York, October 27, 1945.

[1] For a discussion of the experimental technique see A. Nadai and E. A. Davis, "Plastic Behavior of Metals in the Strain-Hardening Range," J. App. Phys. 8, 205–217 (1937).

[2] If the material is compressible, these ratios vary even in the case of simple tension. Indeed, as the tensile force increases, the ratio of lateral contraction to longitudinal extension departs from Poisson's ratio which is valid in the elastic range and approaches the value ½ which expresses the conservation of volume.

components s_1 and e_1. Let us now assume that the stress-strain relation for simple tension or compression is found to be

$$e_1 = c_1 s_1 + c_3 s_1^3 + c_5 s_1^5 + \cdots, \tag{7}$$

with certain constants c_1, c_3, c_5, $\cdots$, and study the possibilities of generalizing this relation to other states of stress and strain. Only odd powers of s_1 have been used in (7), because reversal of the sign of s_1 is assumed to lead to a mere reversal of the sign of e_1.

The powers of s_1 appearing in (7) suggest the use of the powers of the stress deviation in more general stress-strain relations. In the following boldface capital letters will be used to denote tensors. The nth power $\mathbf{S}^n$ of the stress deviation $\mathbf{S}$ is defined as a tensor which has the same principal axes as $\mathbf{S}$, but the principal values s_1^n, s_2^n, s_3^n. The positive integer powers of $\mathbf{S}$ are not independent of each other, however. If $\mathbf{I}$ denotes the unit tensor, the principal values of which are all equal to 1, the so-called Hamilton-Cayley equation[3] for the stress deviation $\mathbf{S}$ states that

$$\mathbf{S}^3 = J_2\mathbf{S} + J_3\mathbf{I}, \tag{8}$$

where

$$J_2 = \tfrac{1}{2}(s_1^2 + s_2^2 + s_3^2), \quad J_3 = \tfrac{1}{3}(s_1^3 + s_2^3 + s_3^3). \tag{9}$$

Indeed, the first principal component of the tensor Eq. (8) is

$$s_1^3 = J_2 s_1 + J_3. \tag{8a}$$

If J_2 and J_3 are substituted from (9), and s_3 is everywhere replaced by $-(s_1+s_2)$ in accordance with (4), the Eq. (8a) is seen to be an identity.

Multiplication of (8) by $\mathbf{S}$ yields[4]

$$\mathbf{S}^4 = J_2\mathbf{S}^2 + J_3\mathbf{S}. \tag{10}$$

Multiplication of (10) by S and substitution of (8) leads to

$$\mathbf{S}^5 = J_3\mathbf{S}^2 + J_2^2\mathbf{S} + J_2J_3\mathbf{I}, \tag{11}$$

etc. *Any positive integral power* $\mathbf{S}^n$ *can thus be expressed as a linear combination of* $\mathbf{S}^2$, $\mathbf{S}$, *and* $\mathbf{I}$, *the coefficients being polynomials in* J_2 *and* J_3 *which are homogeneous in the stress components and of the degrees* $n-2$, $n-1$ *and* n, *respectively.*

While the right-hand side of (7) equals the first component of $c_1\mathbf{S} + c_3\mathbf{S}^3 + c_5\mathbf{S}^5 + \cdots$, it is not possible to generalize Eq. (7) by writing the strain tensor $\mathbf{E}$ in the form

$$\mathbf{E} = c_1\mathbf{S} + c_3\mathbf{S}^3 + c_5\mathbf{S}^5 + \cdots. \tag{12}$$

Indeed, the sum of the principal strains as computed from (12) will not vanish as a rule, in contradiction to (1). When Eq. (7) is generalized, any power of s_1, for instance s_1^5, must be replaced not by the corresponding power $\mathbf{S}^5$ of the stress deviation but by an expression which is homogeneous of the fifth order in the stress components:

$$aJ_2^2\mathbf{S} + bJ_2\mathbf{S}^3 + c\mathbf{S}^5 + dJ_2J_3\mathbf{I}. \tag{13}$$

The coefficients a, b, c, d in the tensor (13) must be determined so that the sum of its principal values vanishes identically, and its first principal value reduces to s_1^5 in the case of simple tension or compression. Since $\mathbf{S}^3$ and $\mathbf{S}^5$ in (13) can be expressed as linear combinations of $\mathbf{S}^2$, $\mathbf{S}$, and $\mathbf{I}$, the expression (13) can be reduced to the form

$$\alpha J_3\mathbf{S}^2 + \beta J_2^2\mathbf{S} + \gamma J_2J_3\mathbf{I}. \tag{14}$$

The sums of the principal values of the tensors $\mathbf{S}^2$, $\mathbf{S}$, and $\mathbf{I}$ equal $2J_2$, 0, and 3, respectively. The sum of the principal values of (14) will therefore vanish whenever $2\alpha+3\gamma=0$. On account of this condition, the expression (14) can be written in the form

$$\alpha J_3(\mathbf{S}^2 - \tfrac{2}{3}J_2\mathbf{I}) + \beta J_2^2\mathbf{S}. \tag{15}$$

Now, $\mathbf{S}^2 - 2J_2\mathbf{I}/3$ is nothing but the deviation of the square of the stress deviation. In the following, this tensor will be denoted by $\mathbf{T}$:

$$\mathbf{T} = \mathbf{S}^2 - \tfrac{2}{3}J_2\mathbf{I}. \tag{16}$$

The coefficients α and β appearing in (15), must still be so determined that the first principal value of this tensor reduces to s_1^5 in the case of simple tension or compression. Then $s_2 = s_3 = -s_1/2$ and Eqs. (9) give $J_2 = 3s_1^2/4$, $J_3 = s_1^3/4$; thus the first principal values of $\mathbf{S}$ and $\mathbf{T}$ are s_1 and $s_1^2/2$, respectively. In the case of simple tension, the first principal value of the tensor (15) thus equals $(\alpha/8 + 9\beta/16)s_1^5$. This reduces to s_1^5 if

$$2\alpha + 9\beta = 16. \tag{17}$$

When the stress-strain relation (7) is generalized, the power s_1^5 may therefore be replaced by any tensor of the form

$$\alpha J_3\mathbf{T} + \beta J_2^2\mathbf{S}, \tag{18}$$

provided that α and β satisfy (17). A similar analysis reveals that *any power* s_1^n *appearing in* (7) *must be replaced by a linear combination of the*

[3] M. Bôcher, *Introduction to Higher Algebra* (The Macmillan Company, New York, 1907), p. 296.

[4] If the tensors $\mathbf{A}$ and $\mathbf{B}$ have the same principal axes and the principal values a_1, a_2, a_3 and b_1, b_2, b_3, respectively, the product $\mathbf{AB}$ is defined as a tensor which has the same principal axes as $\mathbf{A}$ and $\mathbf{B}$, and the principal values a_1b_1, a_2b_2, a_3b_3.

tensors $J_3\mathbf{T}$ *and* $\mathbf{S}$, *the coefficients being polynomials in* J_2 *and* J_3^2, *homogeneous in the stress components and of the degrees* $n-5$ *and* $n-1$, *respectively*. The *numerical* coefficients appearing in these expressions are not entirely arbitrary, but must satisfy a linear equation analogous to (17).

When the powers of s_1 in (7) are replaced by such expressions, and the resulting terms are collected according to whether they contain the factor $\mathbf{T}$ or $\mathbf{S}$, the tensor equivalent of the stress-strain relation (7) is seen to be of the form

$$\mathbf{E}=p(J_2, J_3^2)J_3\mathbf{T}+q(J_2, J_3^2)\mathbf{S}. \qquad (19)$$

Here, p and q are polynomials in J_2 and J_3^2; their coefficients are subject to the condition that e_1 as computed from (19) must reduce to (7) in the case of simple tension or compression.

Since J_2 and J_3^2 are of the even degrees 2 and 6 in the stress components, while the components of the tensors $J_3\mathbf{T}$ and $\mathbf{S}$ are of the odd degrees 5 and 1, reversal of the signs of all stresses in (19) leads to a mere reversal of the signs of all strains. Moreover, since J_2 and J_3 as well as $\mathbf{T}$ depend on the stress deviation rather than on the stress itself, two states of stress which differ only by a state of hydrostatic pressure will produce identical deformations. The stress-strain relation (19) thus fulfills two of the three postulates formulated in Section 1. The third postulate, however, which requires that the ratios of the three principal strains depend only on the ratios of the three principal stresses, is not fulfilled as a rule. In order to conform with this postulate, the stress-strain relation must be of the form

$$\mathbf{E}=f(J_2, J_3^2)[p(J_2, J_3^2)J_3\mathbf{T}+q(J_2, J_3^2)\mathbf{S}], \qquad (20)$$

where f is a suitable function of J_2 and J_3^2, while the polynomials p and q are homogeneous in the stress components, the degree of p being lower by 4 than that of q. The principal values of the expression which appears in brackets in (20) are then homogeneous forms of the stress components. Since the factor f drops out, when the ratios of the principal strains are formed, these ratios depend only on the *ratios* of the principal stresses but not on their absolute magnitudes. Equation (20) thus represents the most general stress-strain relation which can arise under the circumstances specified in Section 1.

3. SPECIAL STRESS-STRAIN RELATIONS

In this section some special cases of the general stress-strain relation (20) will be discussed.

(*a*) If the function f depends on J_2 only, and

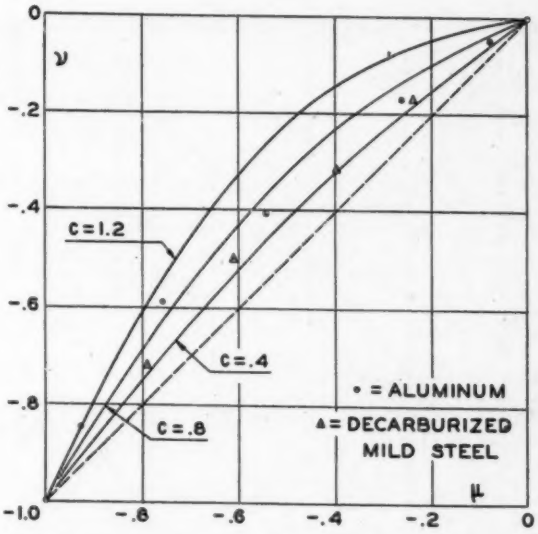

FIG. 1. Test results of Taylor and Quinney. The curves correspond to Eq. (22) for various values of the constant c.

$p=0$, $q=1$, Eq. (20) reduces to

$$\mathbf{E}=f(J_2)\mathbf{S}. \qquad (21)$$

This particularly simple stress-strain relation stipulates that the ratios of the principal strains equal the ratios of the principal components of the stress deviation. W. Lode[5] seems to have been the first to investigate the relation between these ratios experimentally. His results indicated certain deviations from the behavior stipulated by (21), but, on the whole, scattered too much to permit definite conclusions. G. I. Taylor and H. Quinney[6] definitely established such deviations in the case of mild steel, copper, and aluminum. In spite of the fact that the stress-strain relation (21) is not confirmed by the experimental evidence, it is frequently used in theoretical investigations on account of its mathematical simplicity.[7]

(*b*) If the function f depends on J_2 only, and $p=-c$, $q=J_2^2$, Eq. (20) takes the form

$$\mathbf{E}=f(J_2)[J_2^2\mathbf{S}-cJ_3\mathbf{T}]. \qquad (22)$$

This stress-strain relation can be made to fit the

[5] W. Lode, "Der Einfluss der mittleren Hauptspannung auf das Fliessen der Metalle," Forschungsarbeiten a. d. Gebiete d. Ingenieurwesens No. 303, VDI-Verlag, Berlin, 1928.

[6] G. I. Taylor and H. Quinney, "The Plastic Distortion of Metals," Phil. Trans. Roy. Soc. London **A230**, 323–362 (1931).

[7] See for instance A. A. Ilyushin, "Some Problems in the Theory of Plastic Deformations" (Russian, with English summary), Prikladnaia Matematika i Mekhanika **7**, 245–272 (1943).

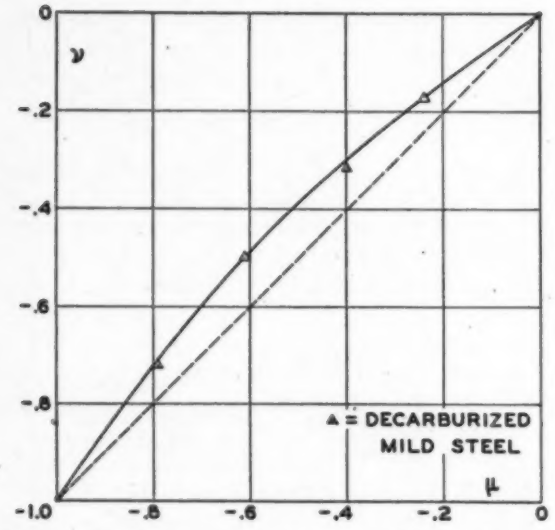

FIG. 2. Test results of Taylor and Quinney. The curve corresponds to Eq. (24) with $c=-.120$, $c'=.466$.

results of Taylor and Quinney by giving a suitable numerical value to the constant c. To represent their results these authors used the parameters

$$\mu=2\frac{s_2-s_3}{s_1-s_3}-1 \quad \text{and} \quad \nu=2\frac{e_2-e_3}{e_1-e_3}-1. \quad (23)$$

Since the factor $f(J_2)$ drops out when the μ and ν are evaluated, the simple stress-strain relation (21) requires that the graph of ν *versus* μ be a straight line; the more elaborate stress-strain relation (22), however, allows a wider variety of forms some of which are indicated in Fig. 1. The results of Taylor and Quinney for aluminum and decarburized mild steel are shown for comparison.

Once the numerical value of the constant c in (22) has been chosen, the function $f(J_2)$ can be determined so as to make (22) agree with an empirical stress-strain diagram for *one* manner of stressing the test specimen, e.g., for simple tension. More freedom in fitting (22) to empirical material is obtained by letting the function f depend on J_3^2 as well as on J_2. Since $J_3=0$ for pure shear ($s_2=0$, $s_3=-s_1$), Eq. (22) can thus be easily made to agree with arbitrary stress-strain diagrams for pure shear as well as simple tension.

(*c*) The expression which appears in brackets in (22) is of the fifth degree in the stress components. If an expression of the seventh degree is used instead, the stress-strain relation

$$\mathbf{E}=f(J_2)[(J_2^3+cJ_3^2)\mathbf{S}-c'J_2J_3\mathbf{T}] \quad (24)$$

is obtained. A stress-strain relation of this type was used by the author in 1937 to represent the results of Taylor and Quinney.[8] For decarburized mild steel the values $c=-.120$, $c'=.466$ prove satisfactory. Figure 2 shows the results of Taylor and Quinney as well as the curve predicted by the stress-strain relation (24) with these values of c and c'.

(*d*) Stress-strain relations which R. W. Bailey[9] had suggested for the creep of metals under combined stresses were applied by E. A. Davis[10] to tests of the kind considered here. In the present notations the first principal component of this stress-strain relation has the form

$$e_1=A[(s_1-s_2)^2+(s_2-s_3)^2+(s_3-s_1)^2]^m \times[(s_1-s_2)^{n-2m}-(s_3-s_1)^{n-2m}], \quad (25)$$

where A is a constant. The remaining two principal components are obtained from (25) by cyclic permutation of the subscripts. To conform with the postulate that reversal of the signs of all stresses leads to a mere reversal of the signs of all strains, the exponent $n-2m$ must be an odd integer; the exponent m can be fractional, however. The general stress-strain relation (20) must contain all relations of the form (25) as special cases. Indeed, on account of (4), the expression in the first bracket on the right-hand side of (25) equals $6J_2$, as is easily verified. The entire expression in front of the second bracket in (25) is therefore equivalent to the factor $f(J_2, J_3^2)$ appearing on the right-hand side of (20). Identification of the second bracket in (25) as a special case of the first principal value of the bracket expression in (20) can easily be accomplished for any given odd $n-2m$. For $n-2m=3$, 5, and 7, for instance, the expression in the second bracket in (25) is found to be the first principal value of $9J_2\mathbf{S}$, $33J_2^2\mathbf{S}-27J_3\mathbf{T}$, and $(129J_2^3-81J_3^2)\mathbf{S}-162J_2J_3\mathbf{T}$, respectively. Bailey's relations for $n-2m=5$ and $n-2m=7$ are thus seen to be special cases of (22) and (24), respectively. The arbitrary constants c and c' appearing in (22) and (24) give a greater degree of flexibility to these stress-strain relations, however, than Bailey's equations possess.[11]

[8] W. Prager, *Mécanique des solides isotropes au delà du domaine élastique* (Gauthier-Villars, Paris, 1937), p. 29–31; see also W. Prager, *Theory of Plasticity* (mimeographed lecture notes) (Brown University, Providence, Rhode Island, 1942), p. 54–56.

[9] R. W. Bailey, "The Utilization of Creep Test Data in Engineering Design," J. Inst. Mech. Eng. 131, 131–269 (1935).

[10] E. A. Davis, "Increase of Stress with Permanent Strain and Stress-Strain Relations in the Plastic State for Copper under Combined Stresses," J. App. Mech. 10, A187–A196 (1943).

[11] *Note added in proof:* Since this paper was submitted for publication, the author noticed that M. Reiner recently discussed the stress-strain relations of non-Newtonian viscous liquids in a somewhat similar manner [Am. J. Math. 67, 350–362 (1945)].

Coil Systems for Producing Transverse and Longitudinal Magnetic Gradients

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A coil system is described which produces very constant magnetic gradients throughout a considerable part of the volume occupied by the coil assembly. One modification produces constant transverse and longitudinal gradients of the field transverse to a long cylindrical region; another modification produces constant transverse and longitudinal gradients of the magnetic field throughout a spherical volume. Gradient data are given for both modifications.

A COIL system has been developed at the Naval Ordnance Laboratory which provides very constant transverse and longitudinal magnetic gradients throughout a volume which is a considerable fraction of the volume occupied by the coil assembly. Such a coil system has been christened the "Gradhelm." It consists of four long identical rectangular coils which are connected in series, as indicated in Fig. 1.

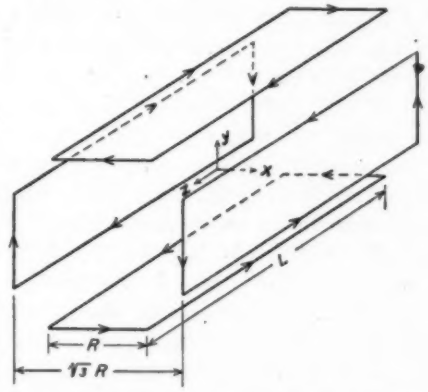

FIG. 1. The Gradhelm. In this orientation, the coil system gives a uniform vertical gradient of vertical field. Rotated 45° about its long axis, it gives a uniform transverse gradient of vertical field.

Two types of gradhelms have been constructed, which may be referred to as:

(a) *Cylindrical*, designed to provide uniform gradients of the field transverse to a long cylindrical object. In this design the length L of the coils is sufficiently great compared to the width R and the length of the object so that the gradients may be computed by considering the wires as infinitely long.

(b) *Spherical*, designed to provide uniform gradients in a region approximately spherical in shape. For this purpose, coils have been constructed with $L=2.9R$; detailed gradient computations are given below for this particular length.

THE CYLINDRICAL CASE

Figure 2 shows a cross section of the coil system. The wires are to be considered as infinitely long in a direction perpendicular to the paper. If H_x and H_y are the components of the field in the x and y directions, this system is designed to give zero field on the axis and constant values of the longitudinal gradients $\partial H_x/\partial x$ and $\partial H_y/\partial y$ in a region near the axis. It simultaneously gives constant values of the transverse gradients $\partial H_p/\partial q$ and $\partial H_q/\partial p$ of the field components H_p and H_q parallel to axes making 45° with the x,y axes. For a two-dimensional system, Maxwell's equations show that at every point

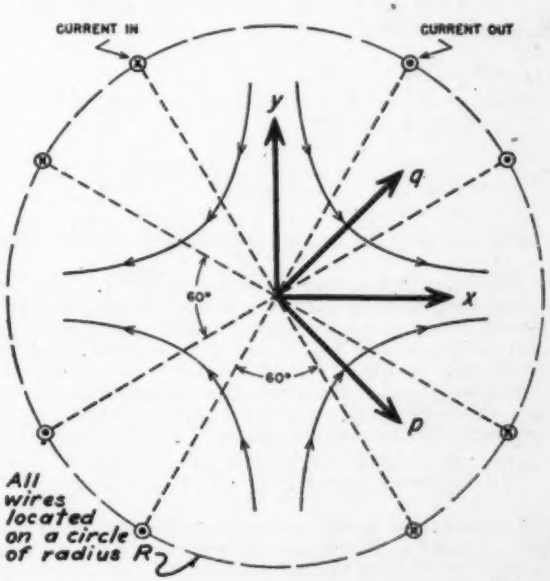

FIG. 2. Cross section of gradhelm coil system shown in Fig. 1. Note: The lines of force indicated above are not computed curves but are intended to be schematic only.

* On leave of absence from the Ohio State University.
† On leave of absence from the Catholic University of America.

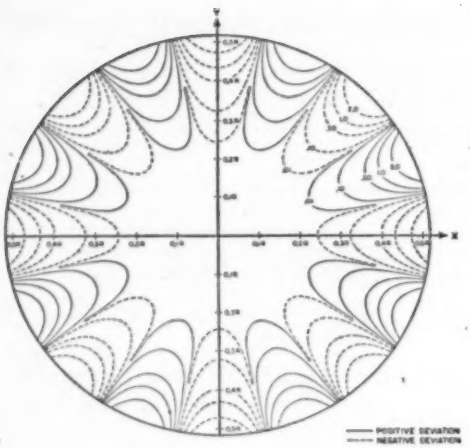

FIG. 3. Deviations of the gradients of Eq. (1) from their values at the center of the "cylindrical" gradhelm of Fig. 2. Deviations are given as percentages. The deviation is less than 5 percent anywhere within the circle shown here.

$$\frac{\partial H_x}{\partial x}=-\frac{\partial H_y}{\partial y}=\frac{\partial H_p}{\partial q}=\frac{\partial H_q}{\partial p}; \qquad (1)$$

hence a study of the constancy of $\partial H_x/\partial x$ gives complete information on the constancy of all of these gradients.

The coil system under consideration gives remarkable uniformity of gradient near the axis of the system. A power series expansion shows the gradients (1) to be constant to within terms of the 8th order in x/R and y/R. For a current of I *amperes* in each wire, and with H in gauss and R in centimeters,

$$\frac{\partial H_x}{\partial x}=\frac{8\sqrt{3}\,I}{10R^2}\left[1-9\frac{r^8}{R^8}\cos 8\phi+13\frac{r^{12}}{R^{12}}\cos 12\phi+\cdots\right], \qquad (2)^1$$

where r, ϕ are polar coordinates such that $x/r=\cos\phi$, $y/r=\sin\phi$. In the bracket of this formula, correction terms of all orders except the 4th, 8th, 12th, . . . vanish because of the symmetric arrangement of four coils; the 4th-order terms are made to vanish by the particular choice of 60° for the dihedral angle subtended by each coil.

Figure 3 shows a plot of the percentage deviation of the gradient components from their central value $8\sqrt{3}\,I/10R^2=1.386\,I/R^2$. It is seen that the gradients are uniform to within 1 part in 1000 (0.1 percent) everywhere within a circle of radius $0.32\,R$; to 1 percent within a circle of radius $0.43\,R$; and to 5 percent within a circle of radius $0.52\,R$.

These values assume perfect accuracy of wire placement. If one wire is displaced from its correct position a distance a, an additional gradient departure from central value is introduced. The ratio of this gradient departure at distance r from the axis to the gradient at the center has a maximum value of $\sqrt{3}\,ra/2R^2$ (plus terms of higher order in r/R and a/R). For the eight wires, the maximum possible relative departure is $4\sqrt{3}\,ra/R^2$, but it is extremely unlikely that the eight contributions to the departure would add together in this way at any point. In practice it does not seem difficult to keep the errors arising from wire placement within one percent in the region $r/R<0.43$ where the error of a perfect coil is less than one percent.

Another item which should be discussed is the matter of departures from the theoretical two-dimensional gradients as the ends of the coils are approached. Computations of gradients along the axis indicate that if the ends are closed as in Fig. 1, the departure is 0.1 percent at a distance of $4.7\,R$ from the plane of the ends and rises to 1 percent at a distance of $2.5\,R$ from this plane. These distances are satisfactorily small for practical two-dimensional coil construction.

THE SPHERICAL CASE

In this case, in which a short coil is used to give an approximately spherical volume of gradient uniformity, end corrections are important. Computations were made for a length $L=2.8977\,R$ (which is $3R\cos 15°$), and this length seems to give satisfactory uniformity.

For a finite coil, coordinates x,y,z are measured in the directions indicated in Fig. 1, from an origin at the geometrical center of the coil system. Coordinates p and q are defined, as in Fig. 2, by a rotation of 45° about the z axis. The

[1] This expression is easily derived by a complex-variable scheme for handling gradients of two-dimensional wire systems. If $z=x+iy$ is a complex number representing any point in the plane of Fig. 2 (not to be confused with the z-coordinate of Fig. 1), and $Z=X+iY$ represents the coordinates of one of the wires, then the gradients created when this wire carries current I *into the paper* can be represented by the complex series:

$$\frac{\partial H_y}{\partial x}+i\frac{\partial H_x}{\partial x}=\frac{0.2\,I}{(Z-z)^2}=\frac{0.2\,I}{Z^2}\left(1+2\frac{z}{Z}+\frac{3z^2}{Z^2}+\frac{4z^3}{Z^3}+\cdots\right).$$

This series can be easily summed over the Z-values of the eight wires of Fig. 2 to obtain the series in (2). To the same accuracy as the longitudinal gradient $\partial H_x/\partial x$ is constant, the transverse gradient $\partial H_y/\partial x$ is found to vanish:

$$\frac{\partial H_y}{\partial x}=\frac{8\sqrt{3}\,I}{10R^2}\left(9\frac{r^8}{R^8}\sin 8\phi-13\frac{r^{12}}{R^{12}}\sin 12\phi+\cdots\right).$$

field is zero everywhere on the z axis. No longer is $\partial H_x/\partial x = -\partial H_y/\partial y$, except on the planes $p=0$ and $q=0$, but at any point

$$\partial H_p/\partial q = \partial H_q/\partial p = \tfrac{1}{2}(\partial H_x/\partial x - \partial H_y/\partial y).$$

At the center of the system,

$$\partial H_p/\partial q = \partial H_x/\partial x = 1.427\ I/R^2. \qquad (3)$$

This is 1.030 times the value for infinite wires. Percentage deviations of $\partial H_x/\partial x$, $\partial H_y/\partial y$, and $\partial H_p/\partial q$, from the central value (3), have been computed at various points in the neighborhood of the origin and are given in Table I. The deviation of any of these gradients is less than 1 percent within a sphere of radius 0.4 R centered at the origin.

We are indebted to Dr. D. H. Rock of the Naval Ordnance Laboratory for supervising the computations for Table I and Fig. 3.

TABLE IA. Percentage deviation of $\partial H_x/\partial x$ from its value at the center.

$q/R\downarrow$ \ $p/R\rightarrow$	0.000	0.075	0.150	0.225	0.300	0.375
			$z=0$			
0.225				−0.25	−0.53	
0.150			−0.11	−0.18	−0.16	
0.075		−0.03	−0.06	−0.11	−0.15	
0.000	0.00	−0.01	−0.03	−0.07	−0.18	−0.55
			$z/R=\pm0.193$			
0.225				−0.20		
0.150			0.01	−0.04		
0.075		0.06	0.04	0.01	−0.01	
0.000	0.08	0.08	0.07	0.04	−0.06	−0.40
			$z/R=\pm0.386$			
0.075		0.28	0.32			
0.000	0.24	0.25	0.28			

TABLE IB. Percentage deviation of $\partial H_y/\partial y$ from its value at the center.

$q/R\downarrow$ \ $p/R\rightarrow$	0.000	0.075	0.150	0.225	0.300	0.375
			$z=0$			
0.225				−0.03	−0.15	
0.150			0.00	−0.01	0.08	
0.075		0.00	−0.01	−0.02	−0.04	
0.000	0.00	−0.01	−0.03	−0.07	−0.18	−0.55
			$z/R=\pm0.193$			
0.225				0.00		
0.150			0.08	0.08		
0.075		0.08	0.08	0.08	0.07	
0.000	0.08	0.08	0.07	0.04	−0.06	−0.41
			$z/R=\pm0.386$			
0.075		0.24	0.25			
0.000	0.24	0.25	0.28			

TABLE IC. Percentage deviation of $\partial H_p/\partial q$ from its value at the center.

$q/R\downarrow$ \ $p/R\rightarrow$	0.000	0.075	0.150	0.225	0.300	0.375
			$z=0$			
0.225				−0.14	−0.34	
0.150			−0.06	−0.09	−0.04	
0.075		−0.01	−0.04	−0.06	−0.10	
0.000	0.00	−0.01	−0.03	−0.07	−0.18	−0.55
			$z/R=\pm0.193$			
0.225				−0.10		
0.150			0.04	0.02		
0.075		0.08	0.06	0.04	0.03	
0.000	0.08	0.08	0.07	0.04	−0.06	−0.41
			$z/R=\pm0.386$			
0.075		0.27	0.29			
0.000	0.24	0.25	0.28			

Data on Rate of Capillary Rise

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(Received September 10, 1945)

General aspects of the dynamics of capillary rise are considered with references to extant theories. A stroboscopic method used to study the rise of a liquid in a capillary tube is discussed. Tables are presented showing the observed heights at various times during the rise for the liquids—water, ethyl alcohol, and glycol in each of three capillaries of different diameters.

INTRODUCTION

BECAUSE of its connection with fluid friction, viscosity, and surface tension, the rate of rise of a liquid in a capillary tube is of theoretical interest. The dynamics of such a flow is also of practical interest because of its bearing on the problem of porous penetration.

When a capillary is dipped vertically into a

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liquid that wets the tube, the liquid at once rises, rapidly at first, then more slowly until a height is reached corresponding to the ordinary static state. The early part of the rise is so rapid that recourse to stroboscopic photography or some similar method must be made to observe it quantitatively.

There are many factors to be considered in a rigorous derivation of a differential equation for the rise in clean capillary tubes of uniform bore. Some of the more obvious ones are listed below:

(1) The rise involves a non-steady-state condition, and, at least in the earlier stages, is impulsive. The fact that a mass of liquid is in motion below as well as above the opening to the capillary must be considered.

(2) The vital factor in effecting the rise is surface tension. However, the question of angle of contact is very pertinent. Does this remain constant during the accelerating rise, or does it vary in a predictable, regular way?

(3) The possible presence of turbulence over some of the column of liquid cannot be ignored despite low values of Reynolds number. We are here dealing with a non-steady-state flow and boundary conditions are important. If the meniscus assumes a concave shape, how can the upward speed of flow be greatest at the center without an adjustment at the boundary? Likewise, on entering the tube itself, the liquid must adjust suddenly to new conditions of flow, and turbulence may result.

(4) Viscosity contributes in producing frictional force, probably in the same sense as in ordinary streamline flow. Slipping along the walls of the tube should be considered.

Recent literature contains three equations governing the flow for a single capillary. These are to be found, respectively, in papers by Peck and McLean,[1] Rense,[2] and Pickett.[3] The first of these equations is derived treating the upward flow of the liquid as following Poiseuille's law. The second of these must be regarded as an empirical equation with one arbitrary parameter. The third equation represents an application of the force laws to the rising column considered as a free body. The first equation is a special case of the third, the latter reducing to the former when the momentum change is neglected. However, none of these equations takes into account all of the four factors listed above, and only in the case of the second equation was an effort made to allow for turbulence. Owing to the uncertainty in some of the constants used, and in the amount of deviation permitted, it is not easy to check experimental results with theory.

In this paper some stroboscopic data will be presented on the rise of three different liquids in each of three capillaries of different diameters. The data will be presented in such form that it may be used to check the equations mentioned above, or any others that may be proposed to explain the dynamics of capillary rise.

[1] R. L. Peck and D. A. McLean, Ind. Eng. Chem. 6, 85 (1934).
[2] Wm. A. Rense, J. App. Phys. 15, 436 (1944).
[3] G. Pickett, J. App. Phys. 15, 623 (1944).

EXPERIMENTAL METHOD

The experimental data required for the establishment of an emperical relation between the level of the liquid in a capillary and the time necessary for it to reach that level made it necessary that the method to be used incorporate both a time scale and some sort of linear scale. The photographic method of recording proved to be the most satisfactory.[4]

For the time scale, a stroboscopic light was made use of in the illumination of the tube. The time interval employed was dictated by the rapidity with which the liquid attained its maximum height. Intervals of 1/10 and 1/20 second were used. The stroboscopic light shone full on the tube directly opposite the camera which rested upon an improvised turntable. The turntable and camera were revolved and at the instant that the camera was in such a position as to have the capillary within its field the latter was lowered so as to just touch the surface of the liquid. From then on the camera continued to revolve at approximately constant angular velocity. A succession of images of the tube appeared on the photographic plate corresponding to the successive light impulses emitted by the stroboscope. The photographic plate was shielded from all light which did not pass through the tube.

Since measurements were to be taken from the photographs, some point or points of reference had to appear on each image and it was necessary that these points be common to all images. To fulfil this requirement, small markings were made on the tubes about 1.5 cm apart. Distances between these markings were accurately measured. With the aid of a micrometer microscope all levels of liquid on the photographs were measured with respect to the images of these markings. In order to reduce these readings to actual heights in any case, the maximum rise of the liquid was photographed on each plate and the height of the liquid in the tube measured with a cathetometer immediately after the photograph was taken. A simple correction to each of the micrometer readings then gave the true height of the liquid in the capillary. (Photographic difficulties pre-

[4] A typical photograph appears in reference 2.

TABLE I. Rise of water in capillaries.

Time (seconds)	Measured height (cm) r =0.0242 cm	r =0.0285 cm	r =0.0350 cm
0			
.05	0.75	1.00	
.10	1.43	1.80	1.78
.15	2.01	2.30	2.23
.20	2.50	2.63	2.56
.25	2.90	2.89	2.70
.30	3.19	3.10	2.99
.35	3.46	3.30	3.14
.40	3.65	3.47	3.28
.45	3.85	3.60	3.38
.50	4.05	3.73	3.48
.55	4.22	3.85	3.55
.60	4.38	3.94	3.59
.65	4.51	4.03	3.68
.70	4.64	4.13	3.74
.75	4.76	4.23	3.78
.80	4.86	4.29	3.82
.85	4.96	4.38	3.86
.90	5.06	4.44	3.89
.95	5.17	4.49	3.91
1.00	5.24	4.55	3.92
1.05	5.32	4.60	3.94
1.10	5.39	4.64	3.97
1.15	5.46	4.67	3.99
1.20	5.52	4.70	4.00
1.25	5.56	4.72	4.01
1.30	5.60	4.76	4.02
1.35	5.64	4.81	4.02
1.40	5.72	4.85	4.03
1.45	5.77	4.87	4.03
1.50	5.79	4.90	4.04
1.55	5.81	4.91	4.04
1.60	5.83	4.93	4.05
1.65	5.85	4.94	4.05
1.70	5.86	4.96	4.06
1.75		4.97	4.06
1.80			4.07
1.85			4.07
1.90			4.08
1.95			4.08
2.00			4.09
2.05			4.09
2.10			4.10
2.15			4.10
	Maximum 6.00	Maximum 5.06	Maximum 4.15

TABLE II. Rise of ethyl alcohol in capillaries.

Time (seconds)	Measured height (cm) r =0.0242 cm	r =0.0285 cm	r =0.0350 cm
.02	0.31		0.36
.07	0.78	0.90	0.86
.12	1.11	1.16	1.06
.17	1.29	1.33	1.19
.22	1.44	1.43	1.29
.27	1.55	1.53	1.39
.32	1.64	1.61	1.47
.37	1.73	1.67	1.52
.42	1.81	1.73	1.56
.47	1.85	1.78	1.57
.52	1.92	1.82	1.59
.57	1.95	1.85	1.61
.62	1.99	1.87	1.63
.67	2.03	1.89	1.64
.72	2.07	1.92	1.65
.77	2.10	1.94	1.66
.82	2.13	1.97	1.67
.87	2.15	1.98	
.92	2.18	1.99	
.97	2.21		
1.02	2.23		
1.07	2.26		
1.12	2.28		
1.17	2.29		
1.22	2.31		
1.27	2.32		
1.32	2.33		
1.37	2.34		
1.42	2.36		
1.47	2.37		
1.52	2.38		
1.57	2.39		
1.62	2.41		
1.67	2.41		
	Maximum 2.42	Maximum 2.12	Maximum 1.68

vented the zero levels from being easily defined on the plates). Images of the meniscus were not especially clear on the photographs. For a given rise, the meniscus lines appeared concave throughout, with no noticeable differences in curvature except possibly a slight flattening near the start of the rise.

The radii of the tubes were measured with a micrometer microscope. The tubes had been cleaned with nitric acid, washed, and well wetted with the liquid in question before being used. Measured radii agreed well with values calculated by means of the static formula from known constants of the liquids and measured maximum heights.

The most difficult task was to fix the zero of the time scale. If the photographs were clear in the region of the initial rise, the scale could at least be fixed to within the stroboscope time interval. But scattering of light from the liquid below the capillary frequently fogged this area. In such cases extrapolation of height *versus* time-interval curves served to locate the zero points. The absolute values of the times given in the tables following may therefore be subject to a slight zero correction though in most cases any error would be less than 0.1 second.

EXPERIMENTAL RESULTS

The results are summarized in Table I for water, Table II for alcohol, and Table III for glycol. The radii given are those measured for the three tubes used. Information that can be obtained from the tables is the height of the column of liquid at a given time after the rise began. Measured maximum heights are also recorded. The times may be subject to a slight zero correction as mentioned above. The temper-

TABLE III. Rise of glycol in capillaries.

Time (seconds)	Measured height (cm) $r=0.0242$ cm	$r=0.0350$ cm	Time (seconds)	Measured height (cm) $r=0.0285$ cm
.3	0.72	0.50	.15	0.35
.4	0.99	0.72	.25	0.60
.5	1.24	0.90	.35	0.91
.6	1.44	1.06	.45	1.13
.7	1.62	1.16	.55	1.30
.8	1.75	1.24	.65	1.45
.9	1.88	1.32	.75	1.54
1.0	1.98	1.38	.85	1.65
1.1	2.07	1.46	.95	1.72
1.2	2.14	1.51	1.05	1.79
1.3	2.22	1.56	1.15	1.86
1.4	2.29	1.61	1.25	1.93
1.5	2.35	1.65	1.35	1.99
1.6	2.41	1.68	1.45	2.04
1.7	2.46	1.72	1.55	2.09
1.8	2.52	1.76	1.65	2.14
1.9	2.59	1.80	1.75	2.18
2.0	2.63	1.83	1.85	2.20
2.1	2.66	1.85		
2.2	2.69	1.87	2.05	2.29
2.3	2.74	1.90	2.25	2.34
2.4	2.79	1.93.	2.45	2.41
2.5	2.82	1.95	2.65	2.46
2.6	2.85	1.97	2.85	2.50
2.7	2.89	1.99	3.05	2.55
2.8	2.93	2.01	3.25	2.58
			3.45	2.61
3.2	3.03	2.08	3.65	2.66
3.6	3.13	2.14	3.85	2.69
4.0	3.21	2.18	4.05	2.72
4.4	3.29	2.24	4.25	2.75
4.8	3.36	2.28	4.45	2.77
5.2	3.42	2.32	4.65	2.78
5.6	3.47	2.35	4.85	2.80
6.0	3.51	2.37		
6.4	3.54	2.39	5.25	2.84
6.8		2.40	5.65	2.87
7.2		2.41	6.05	2.90
			6.45	2.93
			6.85	2.95
			7.25	2.96
			7.65	2.97
	Maximum 3.62	Maximum 2.47		Maximum 3.05

ature in the cases of ethyl alcohol and glycol was 20.2°C, in the case of water, 25.0°C. Surface tension, density, and viscosity of each liquid may be found in handbooks. Velocities and accelerations may be found by plotting first and second differences and smoothing the resulting curves.

Letter to the Editor

On a Novel Form of Refrigerator

JOHN R. ROEBUCK
University of Wisconsin, Madison, Wisconsin
November 1, 1945

MR. A. M. G. MOODY'S "Letter to the Editor" in the September issue of this journal criticizing my article in the May issue needs answering in its nonpersonal part. I shall take up these points in the order in which they occur in his letter.

A superficial examination of Nernst's device as described by Stodola would have shown that it differs radically from mine in design and purpose, so much so that it has not been cited in patent procedure. The "extensive patent art which I *suspect* . . ." has in fact not yielded a fundamental conflict. Kapitza's turbine was actually suggested by Lord Rayleigh some forty years ago, but needed Kapitza's superb skill to make it work. It has no patent conflict with my device.

In his third paragraph Mr. Moody is disturbed by my taking Stodola's figure of 1300 ft/sec. "completely out of context." He has apparently not observed that Stodola uses 1312 ft/sec. in his discussion of Nernst's device referred to above.

I appreciate Mr. Moody's drawing on his experimental and theoretical experience with high rotational speeds to discuss possible speeds. His conclusion, however, falls well below Beams' experience (1256 ft/sec.) with rotating hollow cylinders.[1] My own feeling is that a type of construction which has not been worked with is very difficult to predict. I made no guess myself, but sought a high but possibly attainable limit for the purpose of discussion.

Mr. Moody gives no reasons to support his pessimistic opinion as to the "ultimate" performance. My article gave many reasons for predicting an exceptionally high efficiency. These may be summarized as follows:

(a) A single moving part supported vertically in a thrust bearing and guided by journal bearings while rotating in a partial vacuum.

(b) The frictional work absorption to move a gas through the relatively short distance involved is small.

(c) The work used to move the liquid is not drawn from the supply of work at all but from the heat the liquid absorbs.

(d) The impossibility of withdrawing both liquid and gas exactly on the axis, means the loss of some rotational energy with its conversion into heat. Since the rotational energy falls with the square of the radius, and the radius of exit may be kept relatively small, these losses will be relatively small.

(e) By compressing the gas in the rotor in the presence of adequate cooled surfaces the work cost of the compression will be reduced much below that in the usual cross between adiabatic and isothermal compression taking place in piston compressors.

(f) By employing an adiabatic expansion the heat to be discharged is gathered up along the temperature gradient, and none of it is lifted in temperature except from where it is on this gradient, to the discharge temperature. No heat is first dropped way down in temperature before it is raised to the discharge temperature.

(g) The remaining point concerns the transfer of heat through the tube wall from gas to liquid. First the area of this contact per unit mass flow of gas may be varied within wide limits by varying the length and diameter of the cylindrical rotor, by varying the diameter and length of the pipe carrying the liquid and by varying the number of pipes in parallel. Second, it is well understood now that the heat transferred across such a metal wall is far below that which would be conducted through this wall under the whole temperature difference being used. Thus the major part of this temperature difference is occupied in moving the heat through the boundary layers of the two fluids one on each side of the metal. Efforts to promote this

transfer have been concerned mostly with the effect of turbulence in thinning these boundary layers.

In the rotor case turbulence may be expected to be very great.[2] The force of the radius to which any element of either fluid will be subjected is given by mv^2/r and for a rotor a foot in diameter with a peripheral velocity of 1300 ft/sec. is of the order of 100,000 times its ordinary weight. If a small quantity of heat moves from a small quantity of the hotter gas to a small quantity of the cooler liquid, the gas will rise a little in density and the liquid will drop, both will be shifted out of balance with their surrounding fluids while all parts involved are subject to this enormous force. The cooled gas will move violently out the radius and the liquid violently in. The films on each surface of the metal wall will thus be violently in motion, and the heat transferred through the metal wall will be greatly increased over what would be transferred when the rotor is standing still. Data on the effect of this enormous force on the heat transfer are lacking, and must be obtained before intelligent designs of the rotor can be made.

It may help to enforce the literal meaning of my phrase if I fill it out with more words, thus, "the falling of the pressure due to falling gas temperature lessens markedly the work extracted by the piston" over what would be abstracted in the absence of such a fall in temperature. It is quite common to hear steam described as a better working material for an engine than, for example, naphtha or anesthetic ether, because its temperature holds up better during the adiabatic expansion, and the yield of work per stroke is therefore better. Different gases differ greatly in their temperature changes on comparable adiabatic expansion.

On the other hand, the rotating mechanism invariably abstracts the same amount of work per unit mass of gas—an amount fixed solely by the linear peripheral speed—for the gas to make the step, periphery to axis. This amount of work is not at all affected by the particular condition or the specific properties of the gas itself.

Or, to put it in another way, the adiabatic expansion of a gas in a cylinder is terminated by the attainment of the final volume while in the rotor it is terminated by meeting the energy demand.

Let me also fill out this "mystical" situation with more words. In a gas compression carried out by a piston moving in a cylinder, it is not possible to have during this compression a coil of pipe distributed throughout the compressional space by which to absorb the heat of compression. On the other hand, it is entirely possible to have such a coil of pipe distributed throughout the compressional arm of the bent rotating tube. This is clearly because of the lack of any need for a piston-like surface following up the gas to cause the compression. Nevertheless there is a pressure gradient along the pipe maintained by a force parallel to the radius "without the *immediate* presence of a solid" surface to accomplish it.

I have been unable to find anything bearing on this point in the reference he supplies. I would be very much interested in other actual cases.

In his last paragraph Mr. Moody suggests—like nearly everyone else—that a model should be built. Unfortunately, I have available neither experienced design engineers nor suitable shop facilities. I published the description and analysis in my article, in the hope that its great *promise* of exceptional performance might tempt a group with adequate know-how and facilities to try it experimentally.

[1] Rev. Sci. Inst. 9, 413 (1938).
[2] Beams, Rev. Mod. Phys. 10, 248 (1938).

New Booklets

North American Philips Company, 100 East 42nd Street, New York 17, New York, recently announced the publication of two new booklets, both written by F. G. Firth, research engineer: *Use of Low-Angle X-Ray Scattering in the Study of Catalysts, Viruses and Other Materials*, 4 pages; *X-Ray Diffraction: Basic Theory, Principles and Applications*, 16 pages.

The Arnold Engineering Company, 147 East Ontario Street, Chicago 11, Illinois, has announced the publication of a new illustrated 24-page manual on permanent magnets. It was written by Arnold engineers, and its purpose is to help engineers in industry to utilize better the magnetic and physical characteristics of the Alnico alloys in arriving at efficient design. Request a free copy on your company letterhead.

W. A. Taylor and Company, 7300 York Road, Baltimore 4, Maryland, has issued a completely revised edition of the Taylor combination handbook and catalog, containing both simple and technical explanations of the meaning of *p*H control; specific discussions of the application of *p*H, chlorine and phosphate control to 35 industries; the precautions to be observed in making determinations; and descriptions of all Taylor outfits, including 8 new sets. Copy free on request.

Edmund Salvage Company, P. O. Box 100, Audubon, New Jersey, reports the issuance of a new 12-page catalog on its stock of lenses and prisms. Free on request.

Leeds and Northrup Company, 4934 Stenton Avenue, Philadelphia 44, Pennsylvania, has published Catalog E-54 (2), *Modified Schering Bridge, for Measurements of Dielectric Characteristics*. New photographs, photo-diagrams, and explanatory material have been included to show more clearly the outstanding characteristics and advantages of this direct-reading instrument. Copy free on request.

The International Nickel Company, Inc., 67 Wall Street, New York 5, New York, publishes each month an 8-page bulletin called *Nickel Steel Topics*. The September 1945 issue discusses the use of alloys in the construction of ships, locomotives, railroad tracks, and Bailey Bridges. Free on request.

General Electric Company's "Special Products Digest" for October 1945, published at Schenectady, New York, featured a description and illustration of the emergency kits furnished to Army fliers. One of the most valuable items in the kit is a new dial-type liquid compass. 4 pages.

Nickel Cast Iron News for the fourth quarter of 1945, published by The International Nickel Company, Inc., 67 Wall Street, New York 5, New York, front-pages articles on "Marine Diesels Prove Efficient in Peace as well as in War" and "Alloy Iron Specified to Resist Sea Water." 8 pages.

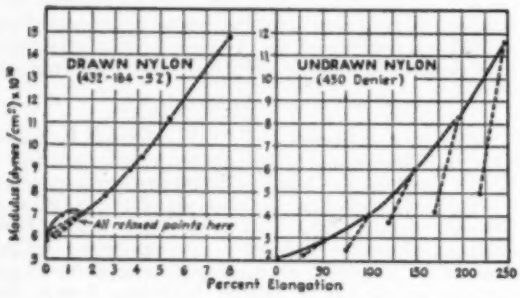
Newsfront, published by Westinghouse Electric Corporation, Pittsburgh 30, Pennsylvania, contains in its December 1945 issue discussions of the gas turbine as used in aircraft; a new three-color warning beam of light for use by airports in assisting pilots to land at night; a diffusion pump for creating vacuums; and an interesting sidelight on the huge atomic research program. 4 pages.

Recent Applications of Physics

Prepared by CLARK GOODMAN, Associate Editor

Material to be included in this section should be submitted to Dr. Clark Goodman, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

Elasticity Measurements The relationship $V_s=(E/\rho)^{\frac{1}{2}}$ is familiar from freshman physics as the velocity of longitudinal waves in a medium of density ρ and adiabatic Young's modulus E. For materials obeying Hooke's law, E may be determined from the slope of the ordinary stress-strain curve obtained by the usual mechanical methods. However, these simple techniques are not applicable to many plastic materials, such as synthetic yarns, Cellophane, and rubber, in which stretching produces a change in structure as well as shape. Instead a high rate of loading must be used so that the deformation takes place rapidly, thereby minimizing the relaxation and plastic processes. This can be accomplished by the use of longitudinal vibrations of relatively high frequency, around 10 kc. By measuring the distance between antinodes of the resulting standing waves, the velocity and hence the Young's modulus can be obtained directly. This method was first applied to elastomers by Meyer and Lotmar,[1] and has recently been improved by Silverman and Ballou.[2] The latter investigators use a half-wave bar of steel (C), activated by two 9.4 kc Brush rochelle-salt crystals (B) connected to an audio-oscillator (A), to drive one end of the stretched fiber or film (E) as shown in the diagram. A definite load is established by hanging weights on the sample after it passes over a small pulley. The whole is assembled on an optical bench (F). A detecting crystal (G) connected through the amplifier (H) to an output meter (I) serves as a sensitive indicator of the small lateral expansion of the sample under the action of the longitudinal standing wave. With the frequency adjusted to resonance the detecting crystal is moved along the optical bench until a peak is observed, meter readings being taken every millimeter. The crystal is then moved on to the next peak, and the distance between is the half-wave-length. Typical results for drawn and undrawn nylon polymer yarn under various conditions of elongation are shown in the accompanying graphs. Check measurements were made on copper and steel wires and compared with observations on plastic materials as follows:



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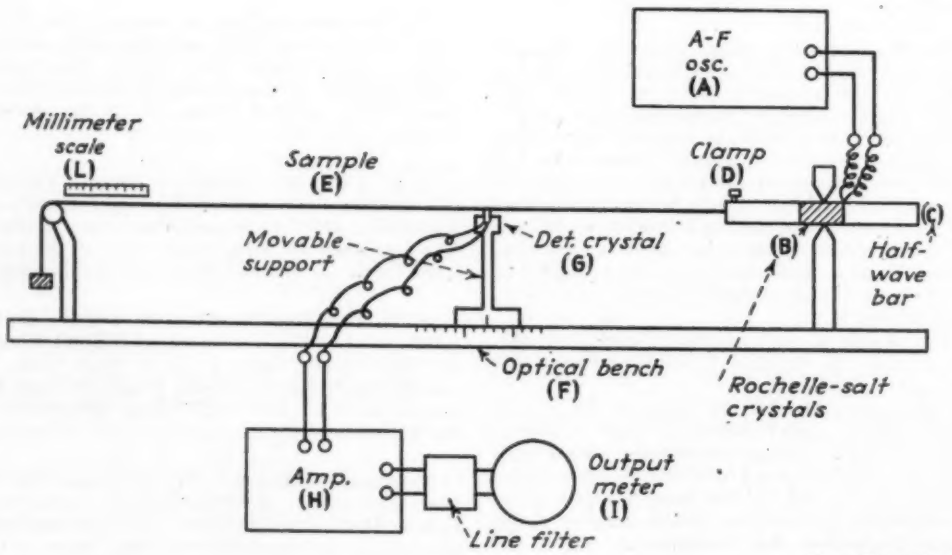
Materials	E in dynes/cm²
Copper-annealed wire	12×10^{11}
Steel piano wire	20×10^{11}
Linen	36×10^{10}
Rayon tire cord	21×10^{10}
Human hair	$6\text{–}7\times10^{10}$
Silk	19×10^{10}
Cellophane film	$5\text{–}12\times10^{10}$

[1] Helv. Chim. Acta **19**, 68–86 (1936).
[2] Electronics, 103–105 (Feb. 1945).



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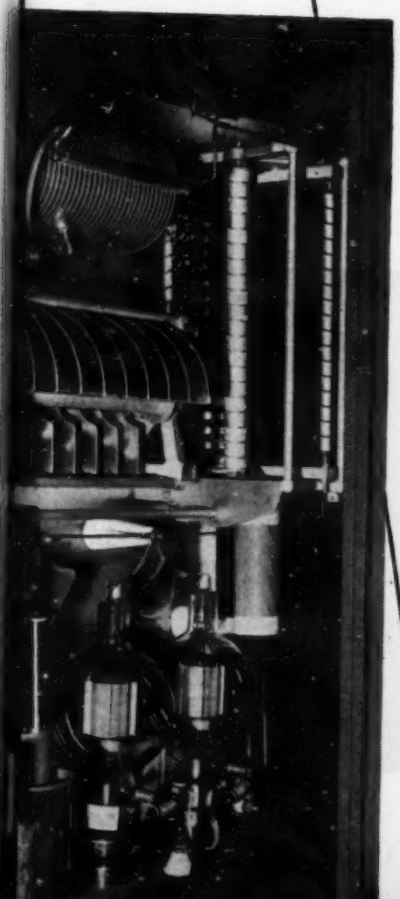

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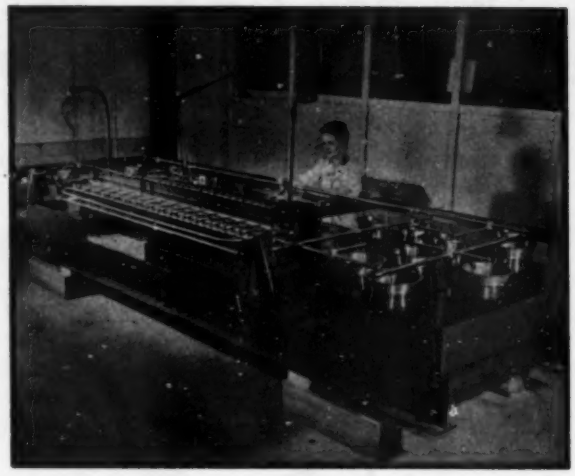
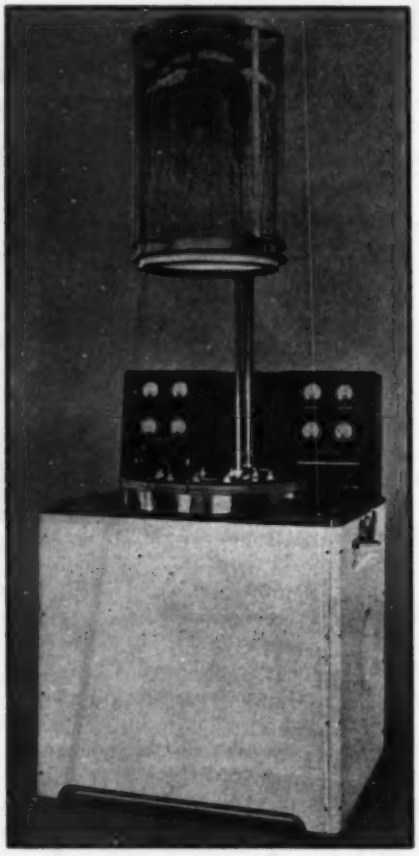
Recent Applications of Physics

Prepared by CLARK GOODMAN, Associate Editor

Material to be included in this section should be submitted to Dr. Clark Goodman, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

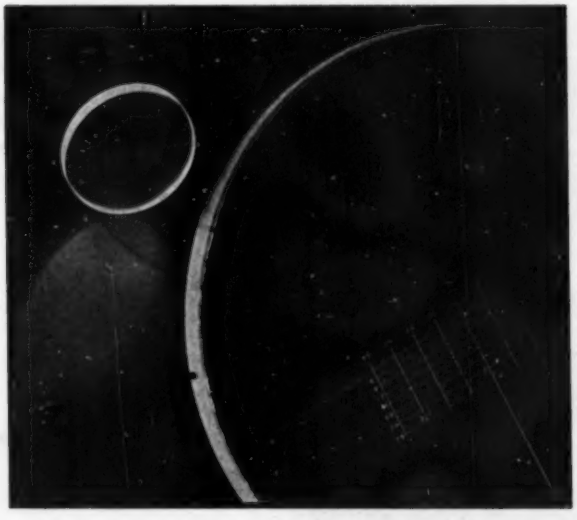
Commercial Coater Only a few years ago the deposition of low reflection films for the production of "invisible" glass was a laboratory curiosity that provoked the attention of cartoonists. Today this procedure finds widespread commercial and military application in improving the optical efficiency of cameras, binoculars, periscopes, and bombsights. To speed the application of this technique and the metallizing of surfaces by evaporation, Distillation Products Incorporated has recently developed the unit shown in the accompanying photograph. It contains such features as a high vacuum valve which enables the diffusion pump to operate continuously, a new simplified direct-reading ionization gauge, and a pneumatic lift for the bell jar.

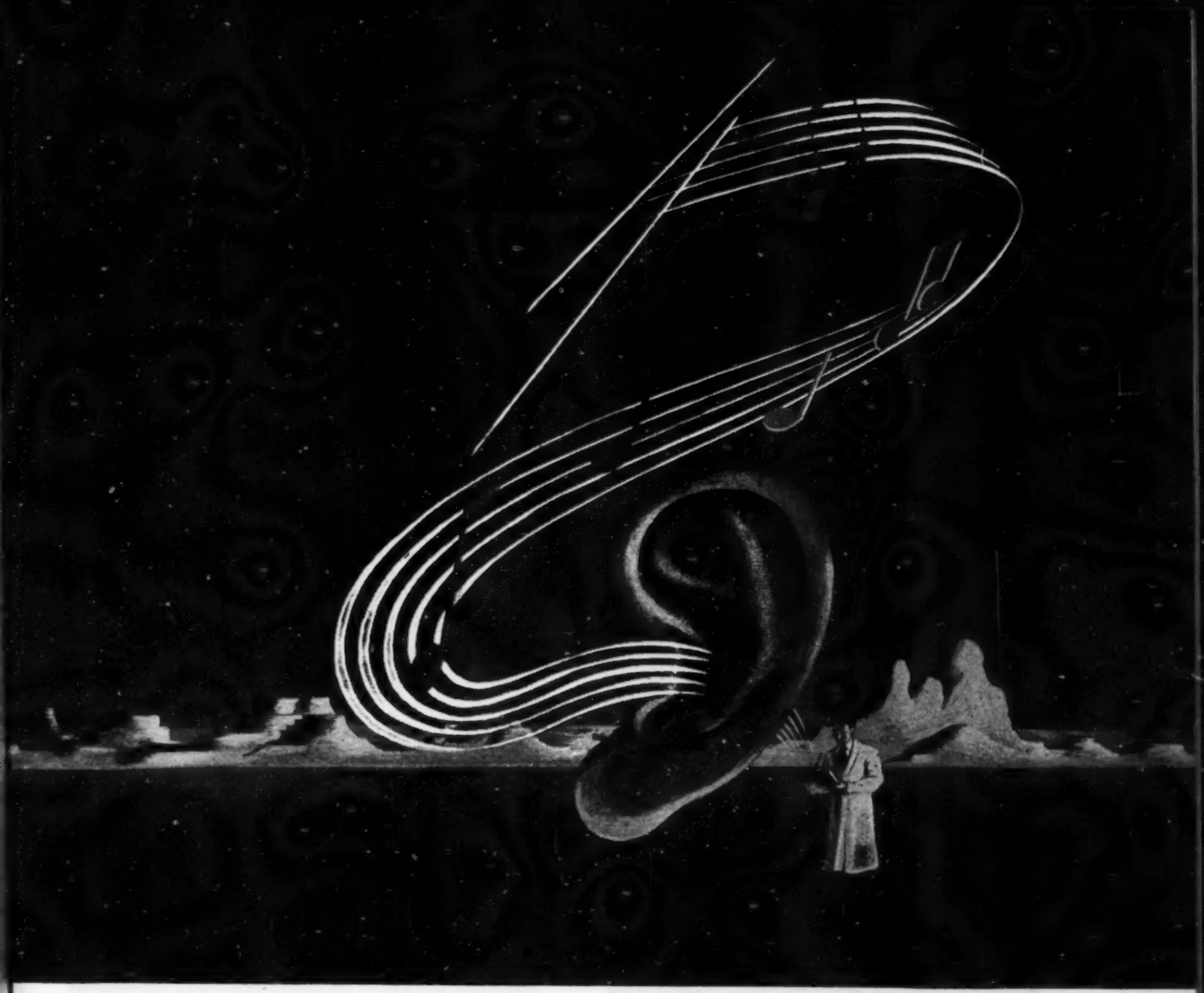




Reticle Ruler Before the war high precision reticles were generally made of fine wires, animal hairs, or even the gossamer threads of spider webs. Such methods are not adapted to the mass production needed to fill the enormous demand for gun telescopes, periscopes, bomb-sights, and fire-control instruments generally. Complicated mil scales, from which estimates of range or size of the target can be made by a simple computation, cannot be constructed accurately of filaments. Such filaments cannot stand the violent accelerations occasioned by the firing of the gun equipped with a telescope. Instead scales are scribed on transparent reticles such as those shown in the accompanying photograph. The lines are filled with black or white pigment depending on the purpose of the instrument.

When World War II began, reticle scales were made by coating glass blanks with wax and scribing them in groups of half a dozen or so with needle styluses carried on the reducing arm of a pantograph machine. Back lash and friction in the bearings and supports of the pantograph arms caused considerable difficulty. Even when the weight of the moving parts was supported on the best roller bearings, the resistance to movement was large enough to require excessive loads at the arm joints to prevent play. The result was jerky motion and unfaithful reproduction of the master plate. Using such methods, one of the largest manufacturers could only produce about 80 perfect units per day. The Hawk-Eye Works of Eastman Kodak has developed a machine that can produce a thousand reticles a day with virtually no scrap. The success of this new pantograph is largely the result of its practically frictionless movement. Steel tubes are used for the arms and all working joints consist of $\frac{1}{16}$ inch ball-and-socket bearings held together only by the weight of the arms themselves. The predominant friction inherent in supporting the moving arms is reduced practically to zero by mounting the structure at 26 key points on aluminum cake pans floating on motor oil. This procedure is similar to that used in ruling engines. By this means 30 reticles can be scribed simultaneously by a single operator such as that shown in the photograph above. The scribing heads hinged to the pantograph arm are supported by nichrome wires.





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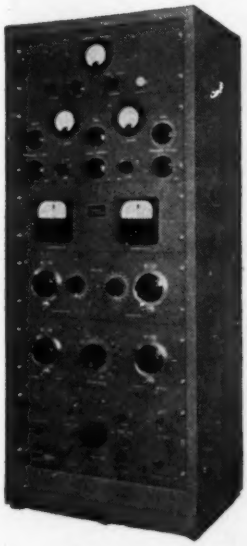

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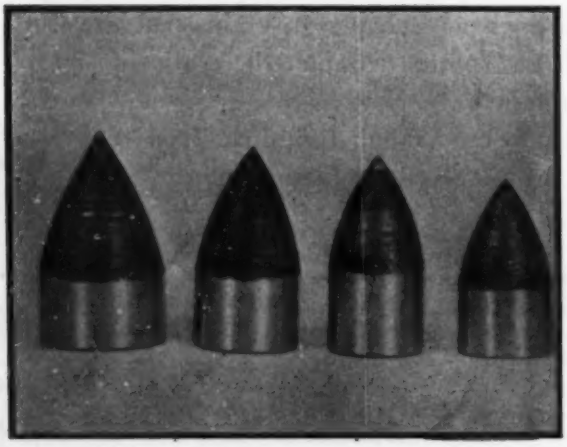
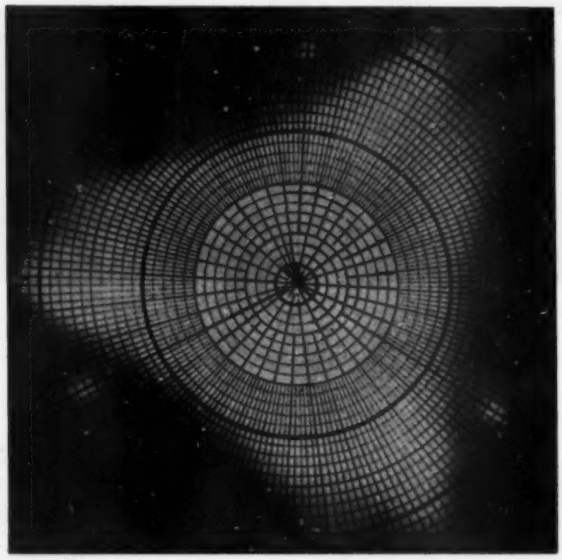
Recent Applications of Physics (continued)

By passing a current of about ½ ampere through the wires the needles are lowered onto the work. When the cutting is finished, the current is turned off and the wires cool and contract, lifting the needles clear. Thus far, over a million reticles have been cut on these machines, and no scale is too complicated to be reproduced in perfect miniature. The lines may be as fine as 0.7 mil in width with figures only 6 mils in heighth.

Gunning for Oil With the war using crude oil at the rate of over a million barrels a day, everything possible is being done to encourage petroleum hunters. As a result, gun perforation of casing strings has become a standard practice in oil-field operations. While this technique is used mainly for tapping formations that were passed by when the older wells were drilled, it is also of value for certain well completions and in subsurface repair work of various kinds. The perforator consists of a heavy steel cylinder, 10 to 20 feet in length, equipped with 30 to 50 demountable gun barrels. These barrels are mounted with their axes perpendicular to the axis of the cylinder. A typical perforator is that developed by the Lane-Wells Company shown in the photograph. The perforator is slung on the end of a steel jacketed electric cable about 3 miles long. In this way it can be lowered down a hole to any predetermined depth and triggered from the surface. The bullets travel radially outward, penetrating the casing, or steel pipe, that lines the well and perforate or fracture the surrounding cement or rock. If oil is present, it can then flow in through these openings. A few of the new ogival-point bullets developed by Lane-Wells are shown. By sealing each barrel at its outer end with an easily penetrated plug, fluid from the well is prevented from entering the barrel. In this way muzzle velocities of 3000 feet per second for 20-gram bullets can be achieved with only 3-inch barrels. Perforations have been successfully accomplished at depths of more than 15,000 feet in which the static pressure exceeded 8000 p.s.i. Firing is controlled electrically on the surface, individual or multiple shots being possible.



Crystallographic Rodometer Prior to the critical step of cutting quartz in the manufacture of oscillator or resonator plates, it is necessary that the material be mounted in an accurately known crystallographic orientation. Based on the earlier work of de Gramont, Cady, and Hubbell, a rapid method has been developed by Holton[1] for axial determinations that can be made accurate to about 15 minutes of arc. Etch figures are produced on one part of the crystal by a controlled process that develops a trigonal set of facets whose directions with respect to the crystallographic axes are functions only of the properties of the crystal examined. The refraction pattern, produced by these facets when a beam of light traverses the crystal, is adjusted to coincide with a prepared circular net outline on the translucent screen of the instrument. The accompanying photograph is the refraction pattern of a left-handed quartz crystal. In addition to defining the handedness and twinning of the crystal, the pattern determines the position and polarity of the three axes.



The current industrial use of the rodometer is for a rapid preliminary setting of the crystal for the first cut which can be used for the final orientation by one quick x-ray examination. Other crystals than quartz can also be subjected to the rodometric method.

[1] G. J. Holton, Electronics, p. 144 (May 1944).

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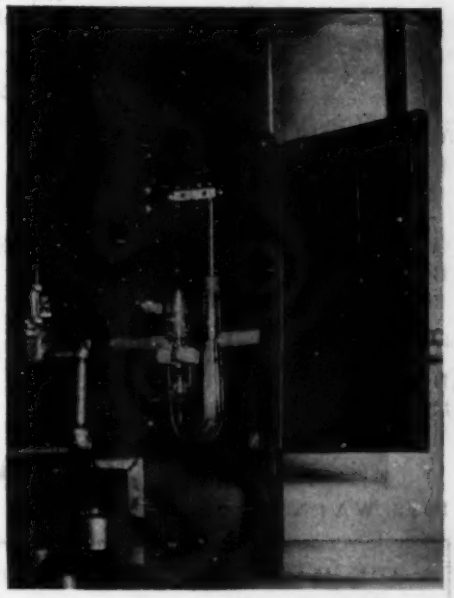

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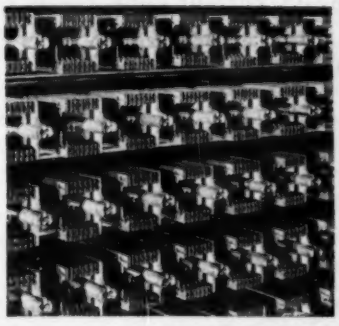

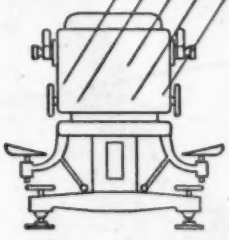

(Left to right) The operator punches the problem data on tape, which is fed into the computer. The solution emerges in the teletype receiver. Relays which figure out the problem look like your dial telephone system.

In designing the gun-control systems which shot down enemy planes, Army ballistic experts were faced by long hours of mathematical calculations.

So Bell Laboratories developed an electrical relay computer. It solved complicated problems more accurately and swiftly than 40 calculators working in shifts around the clock.

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In battle action, Electrical Gun Directors are instantaneous. Such a director helped to make Antwerp available to our advancing troops by directing the guns which shot down more than 90% of the thousands of buzz bombs.

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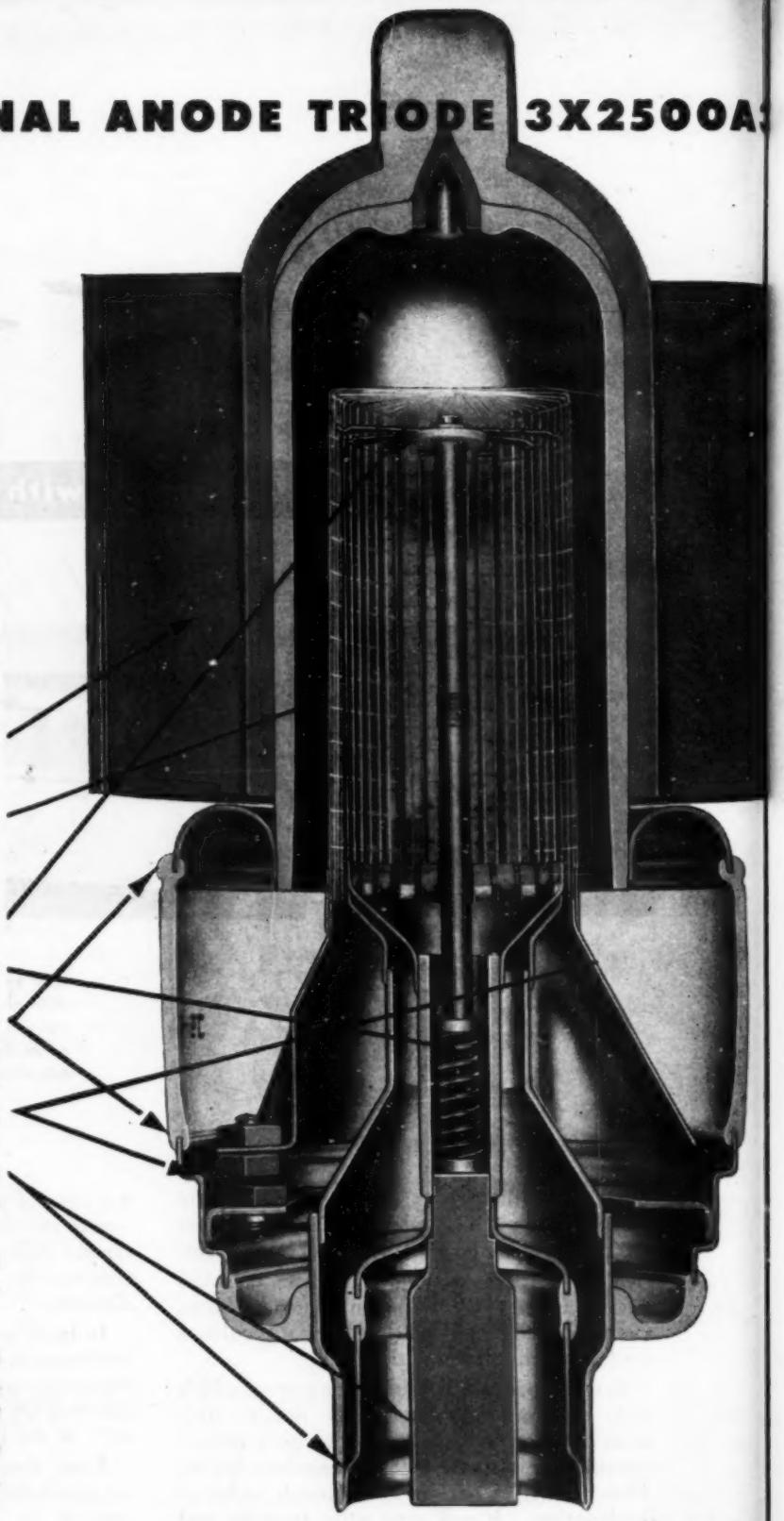

The external anode, conservatively rated at 2500 watts dissipation, has enclosed fins so as to facilitate the required forced air cooling.

Non-emitting vertical bar grid does not cause anode shadows ordinarily created by heavy supports in the grid structure.

Thoriated tungsten filament. Note unusually large filament area, and close spacing.

Filament alignment is maintained throughout life of the tube by special Eimac tensioning method.

New glass-to-metal seals do not have the RF resistance common to iron alloy seals, nor the mechanical weaknesses of the feather-edged types.

Grid ring terminal mounts a cone grid support which acts as a shield between plate and filament.

A coaxial filament stem structure forms the base of the tube. This makes possible proper connections to the filament lines.

Grid and filament terminal arrangements make it possible to install or remove the 3X2500A3 without the aid of tools.

The new mechanical and electrical features of the Eimac 3X2500A3 external anode triode make it valuable for use on the VHF as well as low frequencies. More complete data and information yours for the asking.

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TYPE 3X2500A3 — MEDIUM MU TRIODE

ELECTRICAL CHARACTERISTICS

Filament: Thoriated Tungsten	
Voltage	7.5 volts
Current	48 amperes
Amplification Factor (Average)	20
Direct Interelectrode Capacitances (Average)	
Grid Plate	20 $\mu\mu$fd.
Grid Filament	48 $\mu\mu$fd.
Plate Filament	1.2 $\mu\mu$fd.
Transconductance (i_B=830 ma., E_B=3000 v.)	20,000 μmhos

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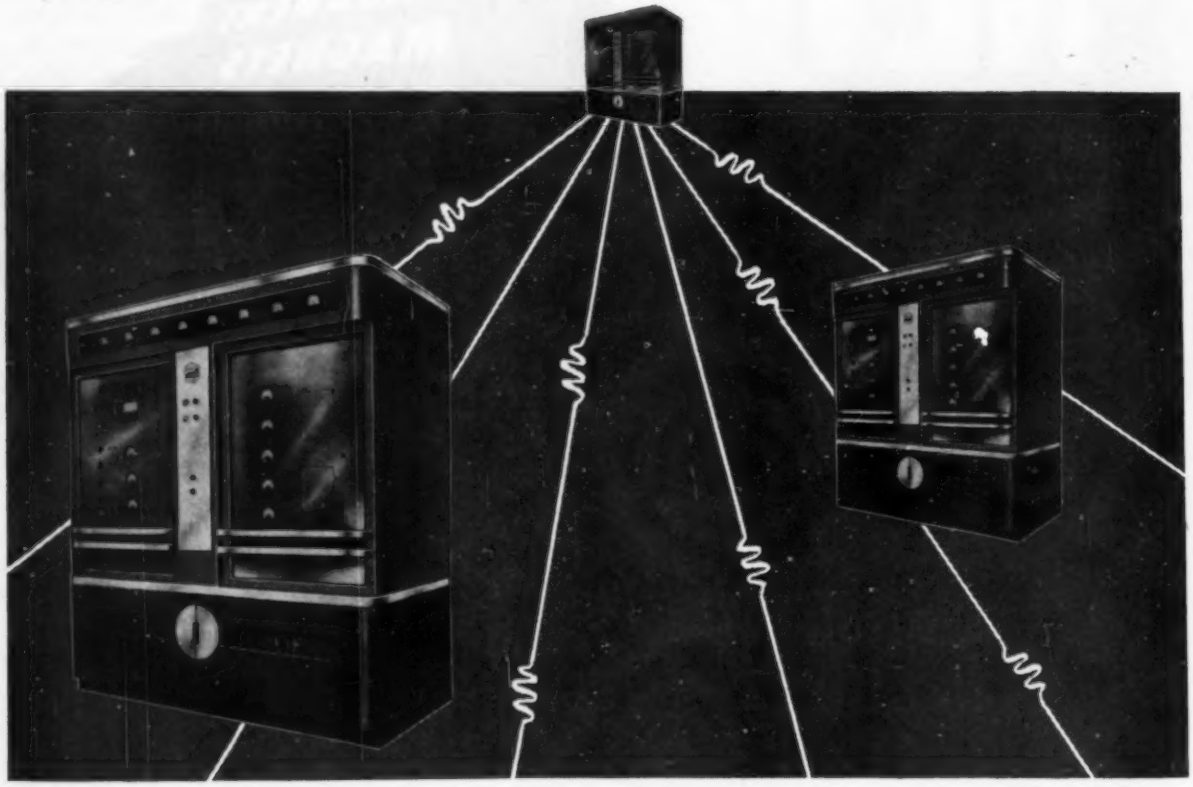

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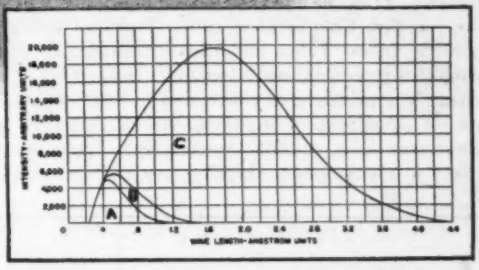
GENERAL. Water-cooled by tap water flowing through ducts in vacuum-cast copper anode. Rayproof. May be operated on either rectified or unrectified voltage. Available in either shockproof or non-shockproof form.

For complete details of this new tube, write Machlett Laboratories, Inc., Springdale, Connecticut.



Wave bands and intensities of X-ray provided through: A, aluminum; B, pyrex glass; C, beryllium

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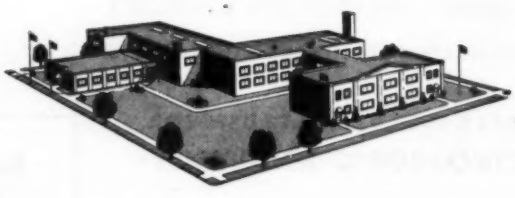

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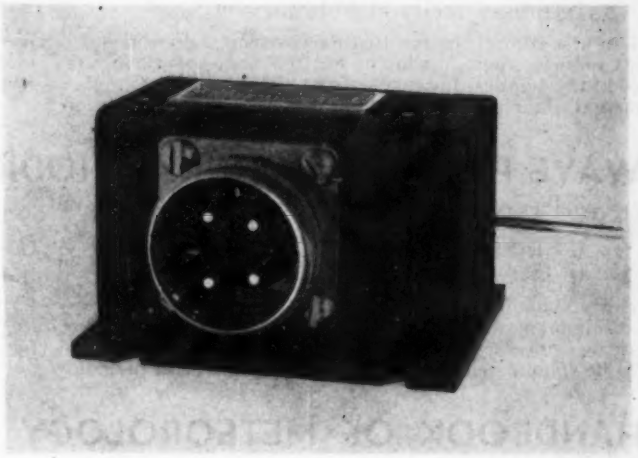

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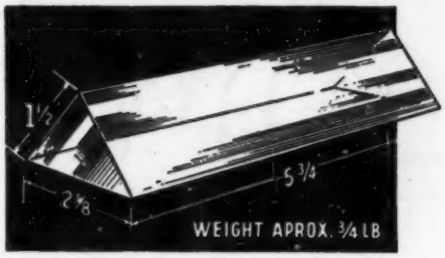

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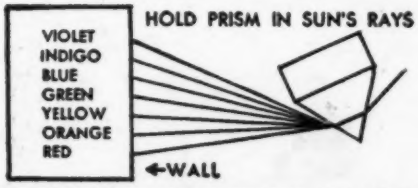

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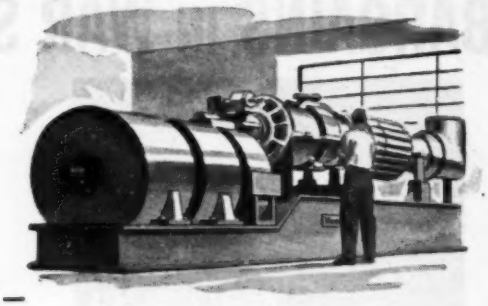

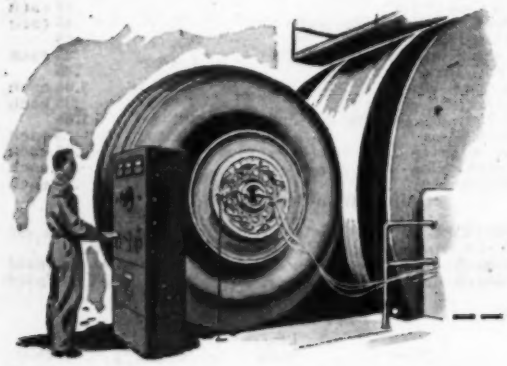

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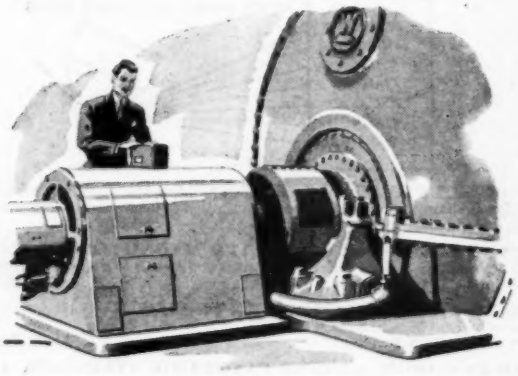

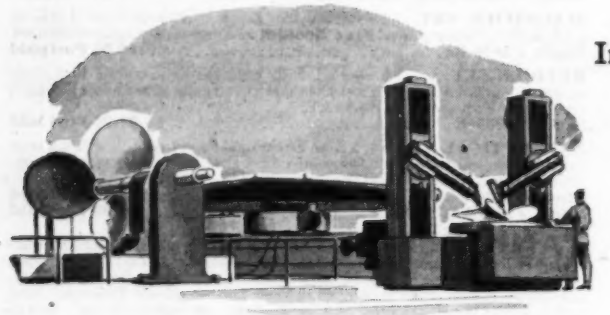

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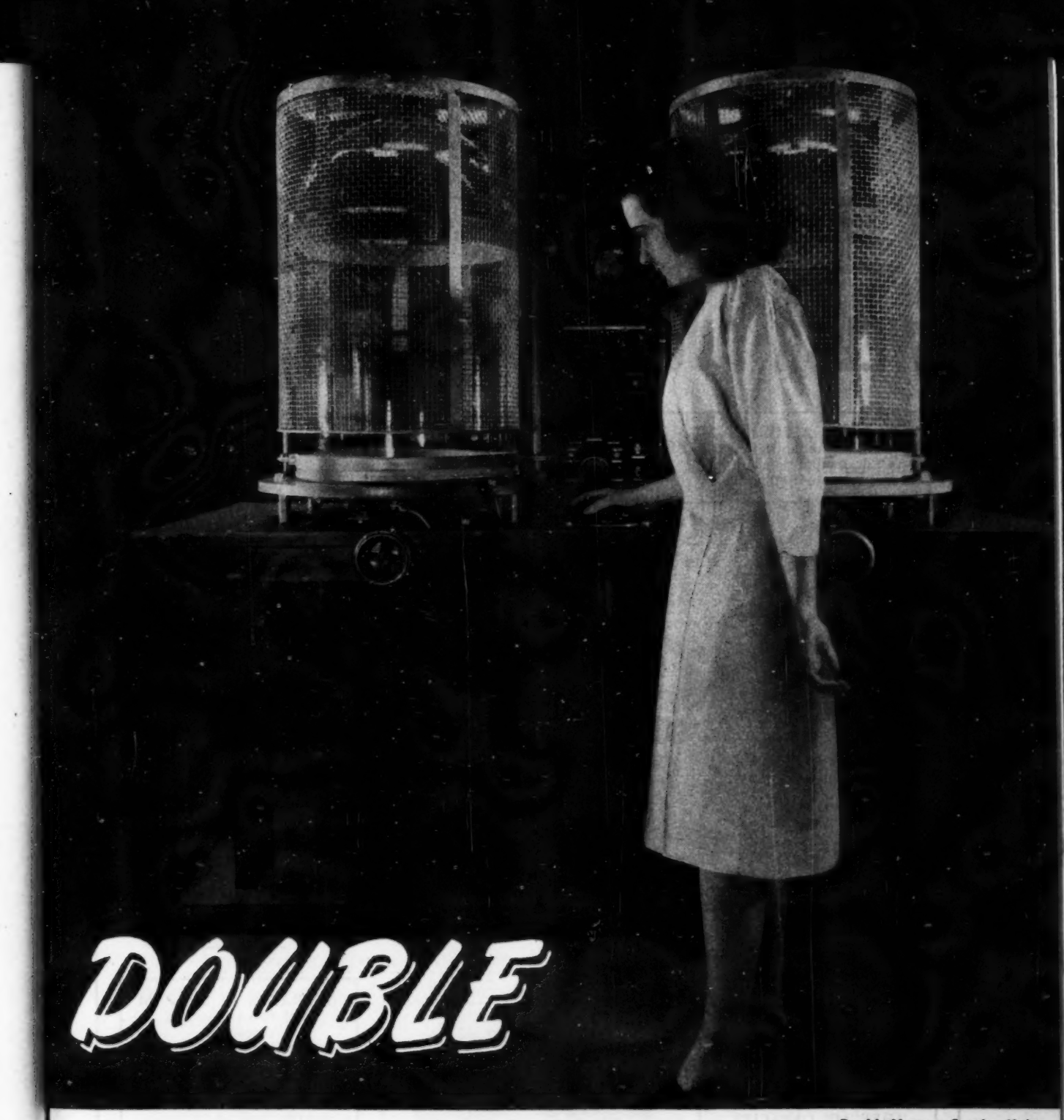

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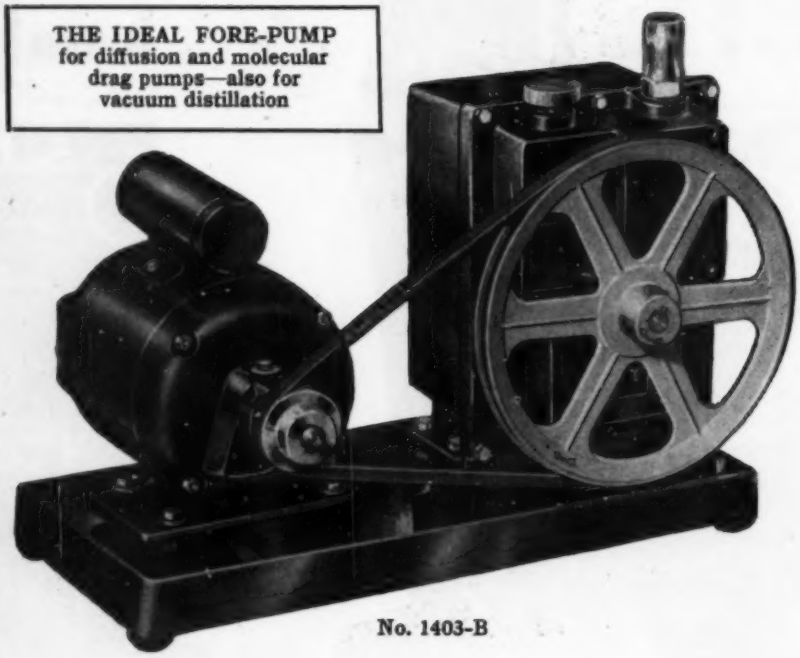

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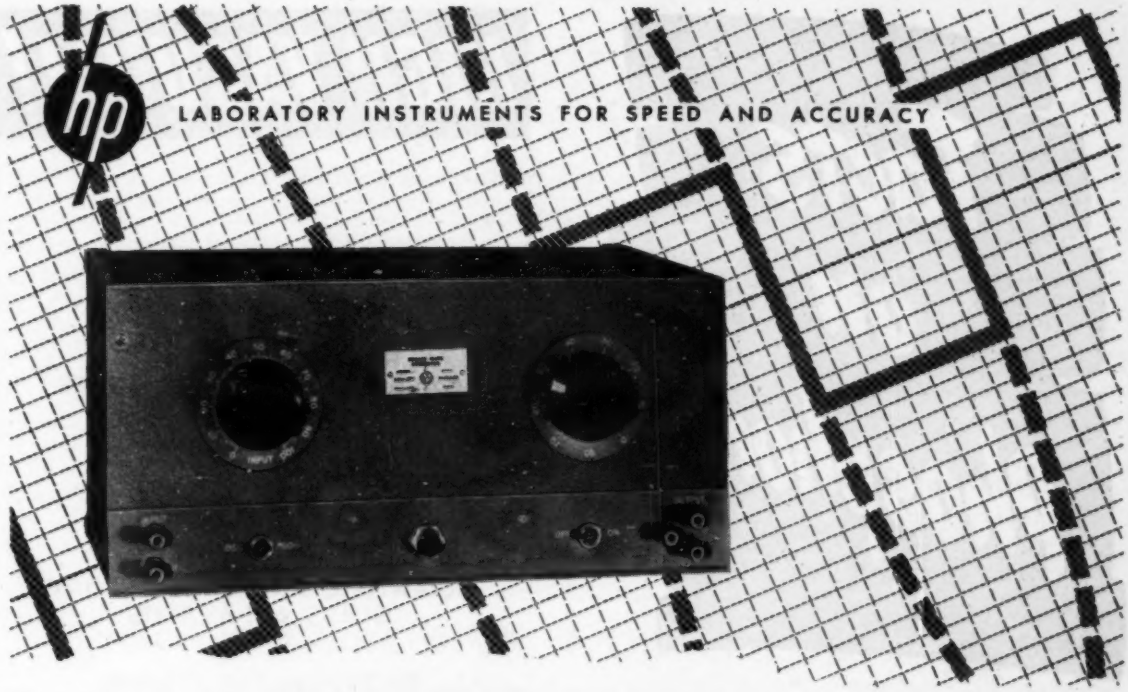

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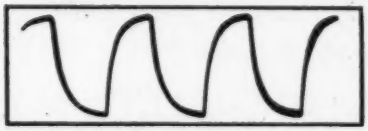

Fig. 1—Shows the square wave distortion caused by poor high frequency response

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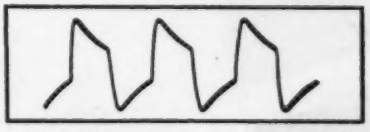

Fig. 2—Low frequency phase distortion serious in television video circuits

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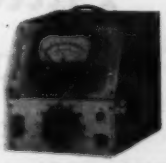

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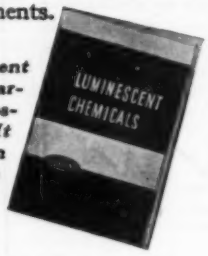

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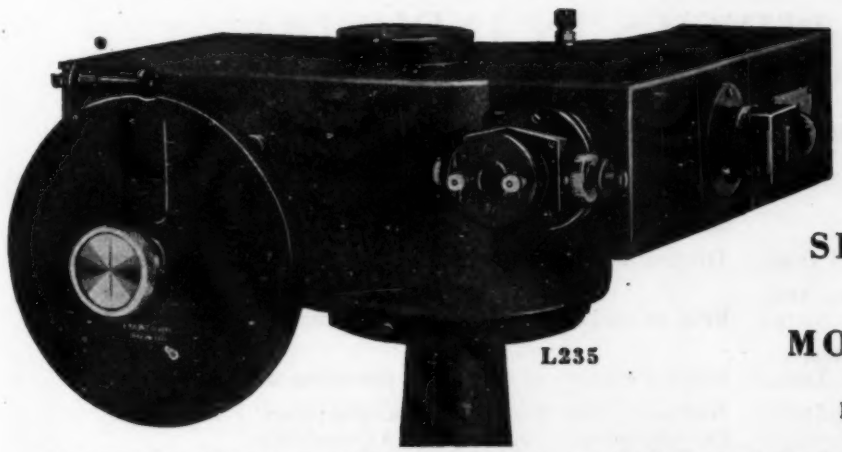

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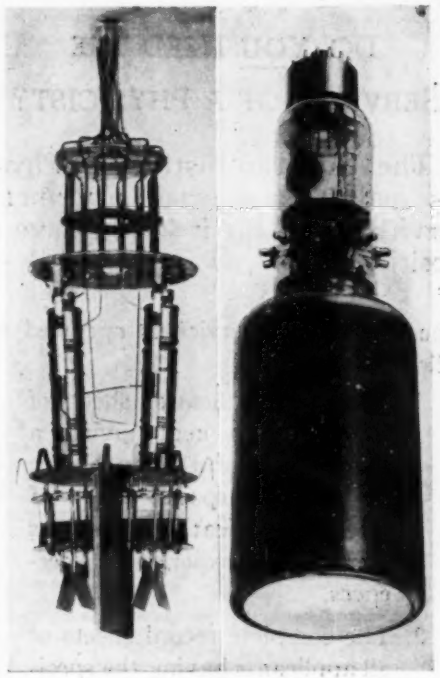

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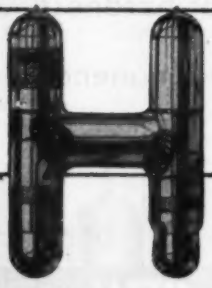

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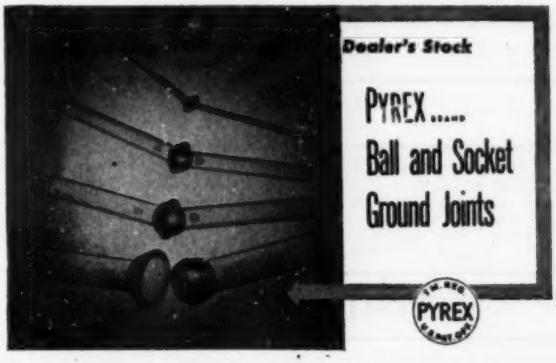

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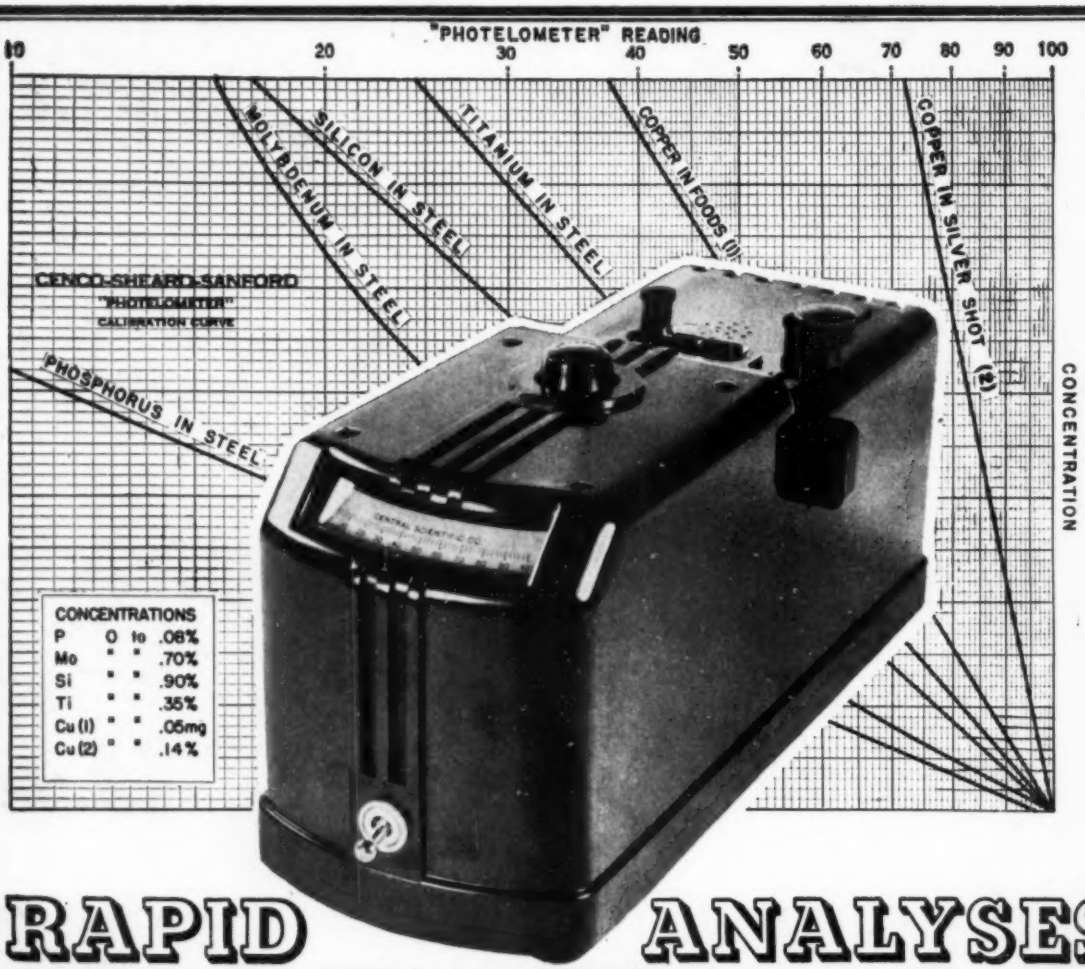

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